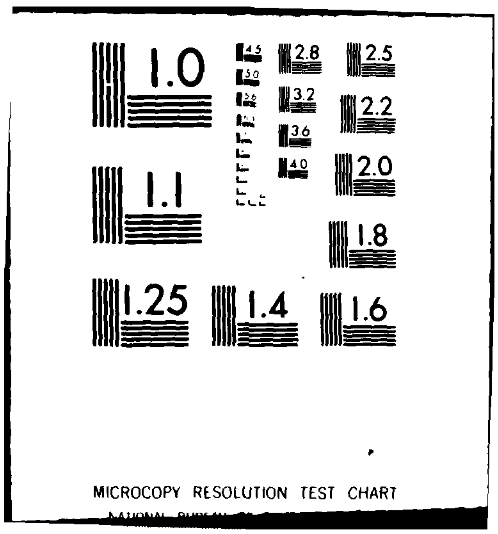
AD-A092 741 ANALYTIC SCIENCES CORP READING MA F/G 17/7
OMEGA SIGNAL COVERAGE PREDICTION DIAGRAMS FOR 10.2 KHZ. VOLUME --ETC(U)
OCT 80 R R GUPTA, S F DONNELLY, P M CREAMER DOT-CG-951480-A
UNCLASSIFIED TASC-TR-3077-2-VOL-1 NL

END
DATE
FILMED
1-81
DTIC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
MICROCOPY RESOLUTION TEST CHART

6

OMEGA SIGNAL COVERAGE PREDICTION DIAGRAMS FOR 10.2 kHz.

VOLUME I. TECHNICAL APPROACH.

10 Radha R. Gupta
Stephen F. Donnelly
Paul M. Creamer
Suzanne Sayer

THE ANALYTIC SCIENCES CORPORATION
One Jacob Way
Reading, Massachusetts 01867

14 TASC-TR-3077-2-VOL-1

12 57

11 October 1980

9 FINAL REPORT. Sep 79-Oct 80

15 DOT-CG-951480-A

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Omega Navigation System Operations Detail
Washington, D.C. 20593

Technical Report Documentation Page

1. Report No.

2. Government Accession No. AD-A092 741

3. Recipient's Catalog No.

4. Title and Subtitle
OMEGA SIGNAL COVERAGE PREDICTION DIAGRAMS FOR 10.2 kHz

5. Report Date
October 1980

6. Performing Organization Code

7. Author(s) R.R. Gupta, S.F. Donnelly, P.M. Creamer, and S. Sayer

8. Performing Organization Report No.
TR-3077-2

9. Performing Organization Name and Address
THE ANALYTIC SCIENCES CORPORATION
One Jacob Way
Reading, Massachusetts 01867

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DOT-CG-951480-A

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
U.S. Coast Guard
Omega Navigation System Operations Detail
Washington, D.C. 20593

13. Type of Report and Period Covered
Final Report
Sept. 1979 - Oct. 1980

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Individual Omega station and composite (Omega Navigation System) 10.2 kHz signal coverage prediction diagrams have been developed for eight times. The diagrams show the global accessibility of "usable" 10.2 kHz signals at eight fixed diurnal/seasonal times for two usable signal access criteria. Criterion I requires: signal-to-noise ratio (SNR) $\geq$ -20 dB (in a 100 Hz noise bandwidth) and $\Delta\phi \leq 20$ centicycles (cec), where $\Delta\phi$ is the modal interference-induced phase deviation in the signal phase relative to the reference signal phase. Criterion II differs from Criterion I in that the SNR $\geq$ -30 dB. Volume I presents the diagram development methodology and contains individual station nighttime modal interference diagrams. Each modal interference diagram identifies regions throughout the world where $\Delta\phi \leq 20$ cec for nighttime propagation conditions.

> or = — delta phi < or =

Volume II presents 64 individual Omega station diagrams (Mercator projection): eight selected coverage times for each of eight stations. Each diagram displays the SNR and $\Delta\phi$ contours for a designated signal access criterion and coverage time.

17. Key Words
OMEGA
Very Low Frequency Propagation
Omega Signal Coverage Diagram
Omega Modal Interference Diagram

18. Distribution Statement
Document is available to the U.S. public through the National Technical Information Service Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

16. ABSTRACT (Continued)

Volume III contains 48 composite coverage diagrams which embody the eight coverage times, two signal access criteria, and three different projections (North and South pole centered Azimuthal Equal Distance, and Mercator). Each diagram displays the global accessibility of usable signals from the system for a designated signal access criterion and coverage time.

Volume IV tabulates the bearing angles of great circles to each Omega station. These angles are computed at latitude/longitude grid points having a uniform spacing of four degrees.

PREFACE

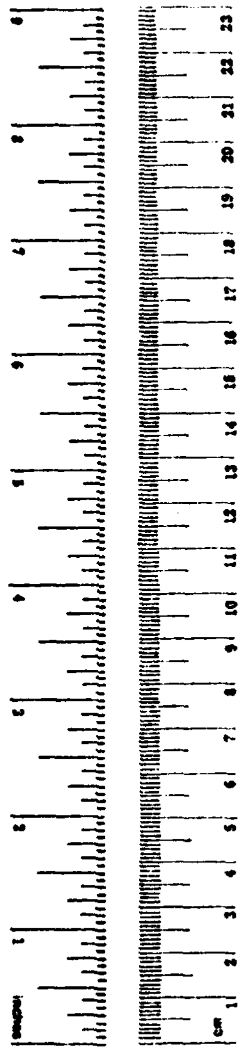
This volume presents the methodology employed to develop 10.2 kHz Omega signal coverage diagrams. Individual Omega station nighttime modal interference diagrams for 10.2 kHz signals are also given in this volume.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

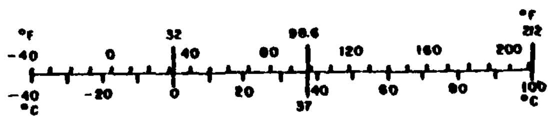


TABLE OF CONTENTS

	Page No.
1. INTRODUCTION	1
1.1 Background	1
1.2 Overview	4
2. SIGNAL COVERAGE TIMES AND MODELS	6
2.1 Introduction	6
2.2 Signal Coverage Times	6
2.3 Modal Interference Effects	8
2.4 Signal Coverage Prediction Models	10
2.4.1 Signal Amplitude Prediction Model	11
2.4.2 Modal Interference Effects Model	15
2.4.3 Atmospheric Noise Amplitude Prediction Model	17
2.5 Geometric Dilution of Precision	18
3. SIGNAL COVERAGE AND NIGHTTIME MODAL INTERFERENCE DIAGRAMS	20
3.1 Usable Signal Access Criteria	20
3.2 Signal Coverage and Modal Interference Calculations	22
3.2.1 Signal-to-Noise Ratio Contours	22
3.2.2 Modal Interference-Free Zone Boundaries	23
3.3 Individual Station Signal Coverage Prediction Diagrams	25
3.4 Composite Signal Coverage Prediction Diagrams	28
3.5 Signal Coverage Availability	31
4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS	34
4.1 Summary and Conclusions	34
4.2 Recommendations	36
APPENDIX A NIGHTTIME MODAL INTERFERENCE DIAGRAMS	37
REFERENCES	47

LIST OF FIGURES

Figure No.		Page No.
1-1	Omega Transmitting Stations	2
2.3-1	Predicted Signal Behavior at 10.2 kHz Along the Nighttime Norway-to-Southeast Propagation Path	9
2.4-1	Phasor Summation of Two Modes	16
2.5-1	Position Fix Geometry Between Receiver and Transmitting Stations 1, 2 and 3	19
3.2-1	Modal Interference Diagram for the Hawaii (C) Station at 10.2 kHz	25
3.3-1	Individual Station 10.2 kHz Signal Coverage Diagram for the Norway (A) Station: February, 1800 GMT	27
3.4-1	Composite 10.2 kHz Signal Coverage Prediction Diagram at February 0600 GMT Based on Signal Access Criterion I--Mercator Projection	30
3.4-2	Composite 10.2 kHz Signal Coverage Prediction Diagram at February 0600 GMT Based on Signal Access Criterion I--Azimuthal Equal Distance Projection Centered at North Pole	31
3.4-3	Composite 10.2 kHz Signal Coverage Prediction Diagram at February 0600 GMT Based on Signal Access Criteria I--Azimuthal Equal Distance Projection Centered at South Pole	32

LIST OF TABLES

Table No.		Page No.
1.1-1	Usable Signal Access Criteria	4
2.4-1	Signal Amplitude Model Functional Forms and Weighting Coefficients	14
3.4-1	Composite Signal Coverage	30
4.1-1	Characteristics of Existing and New Coverage Diagrams	35
A-1	Key to Nighttime Modal Interference Diagrams	37

1. INTRODUCTION

1.1 BACKGROUND

Omega is a very low frequency radionavigation system utilizing phase or phase difference measurements, and is designed to provide a worldwide position fix capability (Ref. 1). The primary navigation signal is at 10.2 kHz although signals at 11.05, 11.33 and 13.6 kHz may also be used for navigation and/ or lane resolution. In the fully operational system, eight transmitting stations distributed uniformly over the globe, as shown in Fig. 1.1-1, will provide a global position fix capability, with an accuracy of two-to-four nautical miles (3.7 to 7.4 km) 95 percent of the time, and under all weather conditions.

Successful utilization of the Omega Navigation System for accurate position fix calculations is based on the availability of "usable" signals from at least three* transmitting stations. Furthermore, these usable signals must be received from directions which provide an acceptable fix geometry. Omega Navigation System signals are considered usable if

- The received signal-to-noise** ratio (SNR) is high enough to permit accurate measurement of phase or phase difference of the received signals

---

*Only two stations are required if the user has a stable (at least one part in 10^{10}) frequency standard.

**Atmospheric noise fields.

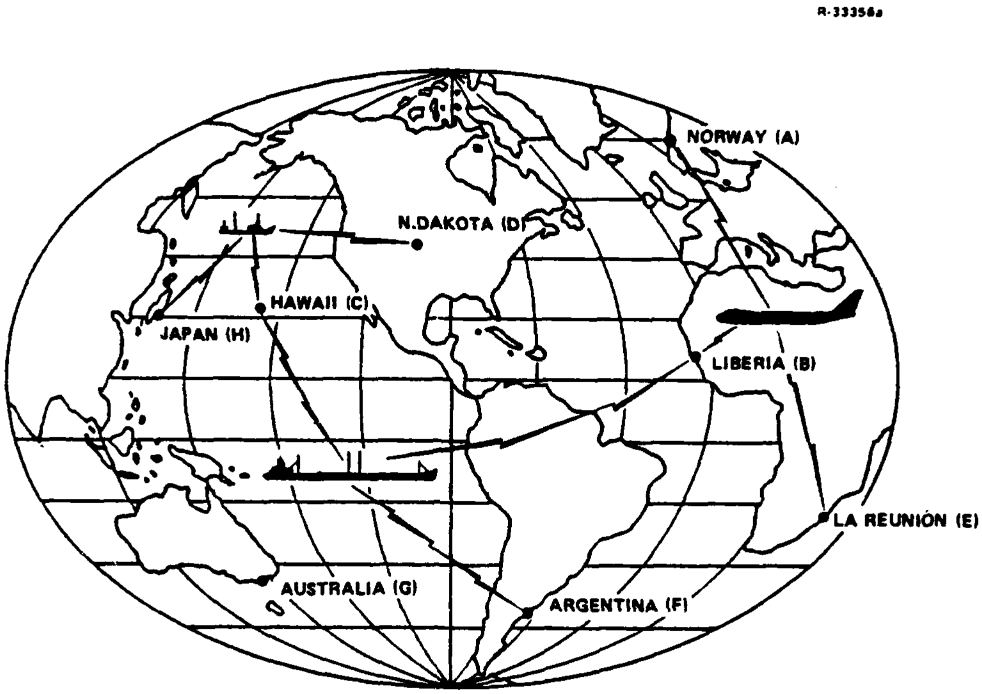


Figure 1-1   Omega Transmitting Stations

- The received signal phase is accurately described by the lowest phase velocity transverse magnetic (TM) mode (reference mode) parameters, required for use in Omega navigation (Ref. 2), as described in Chapter 2.

Deviation of the total (multi-mode) signal phase from the reference mode phase is called the modal interference-induced phase deviation, $\Delta\phi$. The accuracy of a user position fix depends upon the magnitude of phase deviations in the received signals. Because a short-path signal propagation navigation algorithm is commonly employed by Omega receivers, it is also necessary that a position fix signal be associated with a short path (i.e., < 20 megameters (Mm) long). To aid users of the Omega Navigation System in selecting stations with usable signals at 10.2 kHz, composite signal coverage prediction diagrams (Ref. 3) have been made available by the Omega Navigation System Operations Detail (ONSOD). In these diagrams, a station signal is considered usable if

- SNR $\geq$ -20 decibels (dB) (in a 100 Hz noise bandwidth)
- $\Delta\phi \leq$ 13 centicycles (cec).

The -20 dB SNR (100 Hz noise bandwidth) criterion used in the existing diagrams is currently considered by some Omega users to be too conservative. For the latest generation of airborne Omega receivers, which employ to advantage recent advances in both hardware and software technology, a new lower SNR criterion (e.g., -30 dB in a 100 Hz noise bandwidth) is desirable.

The 13 cec signal phase deviation criterion used in the existing diagrams corresponds to a maximum phase difference error of 26 cec (two anticorrelated "modally disturbed" signals) which is equivalent to approximately four kilometers in distance (on a baseline) at 10.2 kHz. This criterion is now considered to be overly conservative and a 20 cec criterion is thought to be more realistic. The 20 cec criterion corresponds with a maximum phase difference error of 40 cec, which is equivalent to approximately six kilometers in distance.

In addition, the existing diagrams only display the predicted global accessibility of usable signals from the Omega Navigation System at two, potential worst and best, local temporal propagation conditions: local summer noon and local winter midnight. There is a growing demand, especially by airborne users, for signal coverage prediction diagrams which display the accessibility of usable signals at a number of global times (e.g., GMT* hours) for each season.

In response to these needs, new coverage diagrams for 10.2 kHz signals are developed as described in this report. Diagrams are drawn for the same two GMT hours, spaced 12 hours

---

*Greenwich Mean Time

apart, for each season. The new usable signal criteria employed are shown in Table 1.1-1. The choice of these criteria will expand the utility of the new diagrams for users of both moderate-performance, and the new high-performance receivers.

TABLE 1.1-1

USABLE SIGNAL ACCESS CRITERIA

CRITERION	SNR	$\Delta\phi$
I	$\geq$ - 20 dB	$\leq$ 20 cec
II	$\geq$ - 30 dB	$\leq$ 20 cec

1.2 OVERVIEW

The development of new 10.2 kHz Omega signal coverage prediction diagrams is comprised of the following major efforts:

- Select a set of eight representative global times (month-GMT combinations) at which signal coverages are to be shown on coverage diagrams
- Construct 10.2 kHz nighttime modal interference diagrams for each Omega station based on the phase deviation criterion identified in Table 1.1-1.
- Develop both individual Omega station and composite (full system) 10.2 kHz coverage diagrams for each selected global time and for each of the two signal access criteria given in Table 1.1-1.
- Identify composite coverage regions which receive three or more usable signals where all three-station combinations yield a geometric dilution of precision which exceeds the threshold value of one kilometer per centicycle

- Prepare tables of bearing angles of great circles from latitude/longitude grid points to each Omega station.

The results of these efforts are presented in four volumes. This volume presents the technical approach for developing the signal coverage prediction and nighttime modal interference diagrams. Sample coverage prediction diagrams and the eight nighttime modal interference diagrams are also contained in this volume. A set of 64 individual station diagrams for the eight selected times and eight stations are given in Volume II. The set of 48 composite diagrams for the eight times, two usable signal access criteria and three projections (Mercator, North and South Pole centered Azimuthial Equal Distance) are contained in Volume III. The bearing angles of great circles to each Omega station are given in Volume IV. These angles are computed at latitude/longitude grid points having uniform spacing of four degrees.

Chapter 2 describes the approach employed to select the eight global times for which coverage is displayed. Chapter 2 also discusses the modal interference mechanism and the semi-empirical model used to predict modal interference effects, and summarizes the semi-empirical signal amplitude and noise amplitude prediction models required for computing signal-to-noise ratio at any time and location on the surface of the earth. The methodology for computing signal-to-noise ratios and modal interference-induced phase deviations, which together determine the usability of a signal, and the procedure for constructing individual station and composite signal coverage diagrams, are described in Chapter 3. Samples of nighttime modal interference diagrams, individual station signal coverage diagrams and composite signal coverage diagrams are also given in Chapter 3. The coverage diagram development effort is summarized in Chapter 4 along with conclusions and recommendations. The full set of nighttime modal interference diagrams is given in Appendix A.

2. SIGNAL COVERAGE TIMES AND MODELS

2.1 INTRODUCTION

Omega signal coverage prediction diagrams display the predicted global accessibility of usable signals at a selected time based on a given usable signal access criterion. The usable signal access criteria involve threshold values for both the signal-to-noise ratio and the modal interference-induced deviation in the signal phase. Preparation of a coverage prediction diagram requires computation of signal-to-noise ratios (i.e., signal and noise amplitudes) and modal interference-induced phase deviations at a number of worldwide computation points at the selected time. This chapter describes the procedure followed to select the desired set of eight fixed global times. The prediction models which are used to compute the signal and noise amplitudes, the mathematical formula for computing the geometric dilution of precision for a three-station hyperbolic navigation position fix, and modal interference-induced phase deviations are also presented in this chapter.

2.2 SIGNAL COVERAGE TIMES

A best-possible set of eight coverage times consisting of a month quartet (four months of the year spaced three months apart) and a GMT pair (two GMT hours spaced 12 hrs apart) is used to display the worldwide seasonal and diurnal variations in the accessibility of predicted signal coverage. One of the GMT hours on the 15th day of a chosen month defines one of the eight coverage times. The best set is selected, as described

below, to minimize adverse terminator* effects on transmitted signals by maximizing the minimum station-terminator distance.

First, the eight station-terminator distances (one for each Omega station) are computed for each of the 24 GMT hours on the 15th day of each month. The 24 GMT hours contain 12 GMT pairs of hours spaced 12 hours apart. Second, for each month and each of the 12 GMT pairs, the smallest of the 16 station-terminator distances associated with the two GMTs (of the pair) and eight stations is extracted. This value represents the smallest distance between any station and a terminator for the particular month and the GMT pair. For each of the 12 GMT pairs, this process results in a set of 12 values, one for each month. Third, within each of these sets, three quartets of values associated with the three possible month quartets are formed. Fourth, the smallest value is extracted from each of these quartets. Finally, of the 36 such smallest values formed over the 12 GMT pairs, the largest value is chosen. The GMT pair and month quartet associated with this largest value constitute the best selection. The smallest station-terminator distance associated with this choice is larger than the smallest station-terminator distance associated with any other selection.

Based on the above coverage time selection procedure, GMT hours of 0600 and 1800 for the months of February, May, August and November are selected as the signal coverage times. The smallest station-terminator distance exceeds 700 km for all of the selected times.

---

*The solar zenith angle equal to 90° defines a day/night terminator along a signal path.

2.3 MODAL INTERFERENCE EFFECTS

The propagation of Omega signals takes place in the space between the earth's surface and the (D-region) ionosphere, often referred to as the earth-ionosphere (EI) waveguide. The total signal propagating in the EI waveguide along a given prediction path is conveniently described as a sum of the "characteristic modes" (or electromagnetic wave field patterns) of the waveguide. The locally-varying electromagnetic properties (e.g., ground conductivity, geomagnetic field direction and solar illumination) of a signal path determine the properties of the component modes and hence the (resultant) total propagating signal. Except in the near-field region* of a transmitting station and along nighttime signal paths at certain azimuths, Omega signal behavior along daytime or nighttime paths can be adequately approximated by a single dominant mode. The dominant mode is the strongest amplitude mode for a given path and is usually identical to the first transverse-magnetic (TM) mode (i.e., the lowest phase velocity TM mode) of the path; it is called Mode 1 or the reference mode. The phase of the Mode 1 signal varies slowly and almost linearly with distance. It is this Mode 1 phase linearity with distance which is the basis of Omega navigation.

In the near-field region of a transmitting station and also along nighttime signal paths at certain azimuths, especially paths emanating from low-magnetic-latitude Omega stations, there is usually not a single mode which can be considered dominant. Instead, the propagating signal is characterized by several modes along these paths. Because different modes have different phase velocities, the amplitude and phase of the total (multimode) signal vary in an oscillatory fashion with distance. The oscillatory behavior (typically quasi-periodic with a period

*A transmitting station's near-field region typically extends to 500 km from the station, under the 20 cec phase deviation criterion.

of about 1000 km) is commonly referred to as resulting from "modal interference" effects. These interference effects are denoted as daytime or nighttime effects depending upon the solar illumination over the modal interference path in question. An example of theoretically-predicted (Ref. 4) modal interference effects along a Norway-to-Southeast signal path is shown in Fig. 2.3-1. In this figure, modal effects are largest at the transmitting station and continue to be significant to distances of up to about two megameters from the station. Beyond this point, the total signal along the path (see Fig. 2.3-1) can be considered to be predominantly the Mode 1 signal.

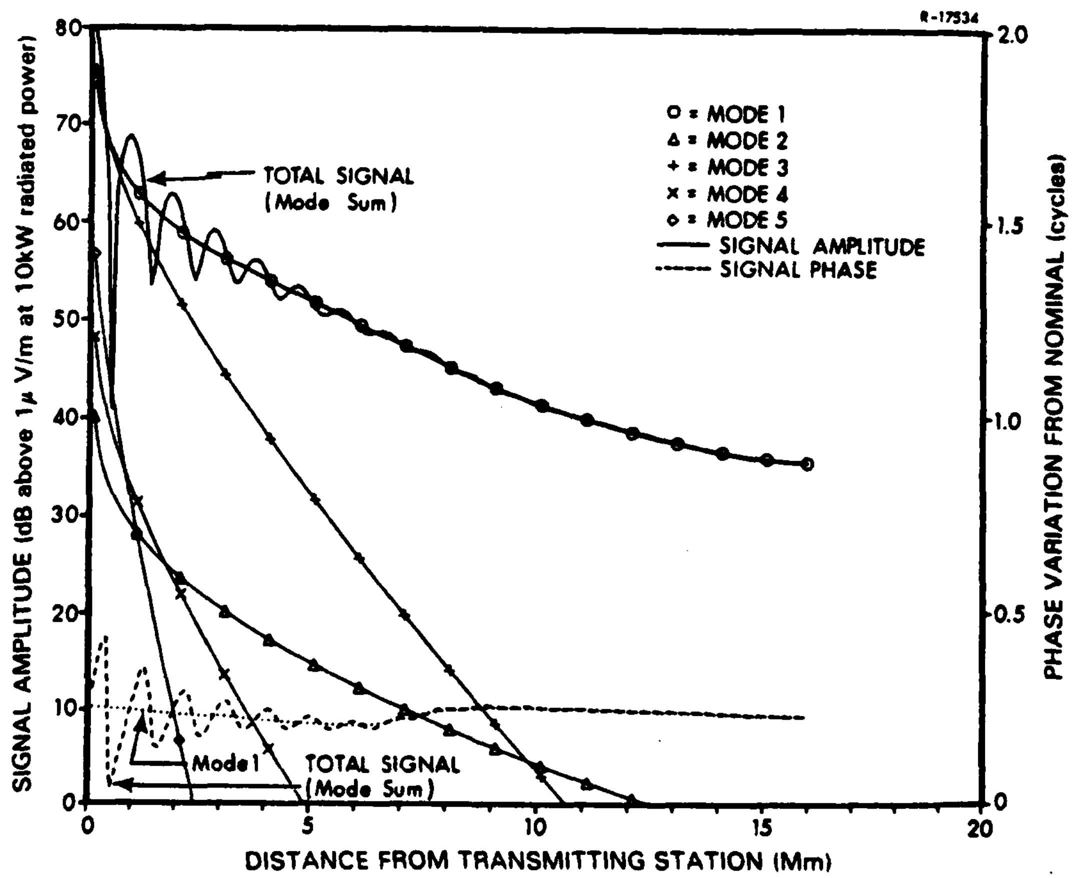


Figure 2.3-1 Predicted Signal Behavior at 10.2 kHz Along the Nighttime Norway-to-Southeast Propagation Path (Nominal Phase Refers to Free Space Propagation)

The utility of the Omega Navigation System depends on the accessibility of three or more transmitting station signals for hyperbolic navigation (or two stations with a stable time standard) each of which has sufficient signal-to-noise ratio and can be adequately described by its Mode 1 behavior. Therefore, daytime or nighttime signals which are suspected to be "severely" corrupted (or disturbed) by modal interference effects, similar to the effects observed close to the transmitting station in Fig. 2.3-1, are unusable even though they may have sufficient signal-to-noise ratios to permit signal tracking. Omega station signal coverage prediction diagrams must therefore identify regions with daytime or nighttime illumination where modal interference effects are expected to be severe.

In addition to the daytime or nighttime modal interference described above, similar effects are also observed when the signal transits the day/night terminator along a mixed (part daytime and part nighttime) path. This type of interference is a result of "mode conversion" at the terminator where energy associated with the mode incident on one side of the terminator is "converted" or distributed among several other modes on the other side of the terminator. These effects can be severe along certain mixed paths, especially those with an east-to-west segment crossing the geomagnetic equator.

2.4 SIGNAL COVERAGE PREDICTION MODELS

Development of Omega signal coverage prediction diagrams requires a signal amplitude model, a modal interference-induced phase deviation model and an atmospheric noise amplitude prediction model to provide signal coverage data as a function of both space and time. These models are described in this section.

2.4.1 Signal Amplitude Prediction Model

A number of theoretical models (Ref. 4 through 11) are available, but all are limited to either daytime or nighttime illumination over signal path. Of the available theoretical models, Budden's (Ref. 11) full-wave waveguide theory-based model, known as IPP (Refs. 4 through 6), is the most widely used theoretical model for predicting the amplitude and phase of the various modes and the resultant multi-mode signal propagating along a daytime or nighttime path.

Because the IPP model cannot provide predictions over non-uniformly illuminated paths, a semi-empirical signal amplitude prediction model is used to develop the coverage diagrams. This model combines IPP-derived signal amplitude sub-models* for daytime and nighttime paths (Ref. 13), and empirically-derived diurnal sub-models which are functions of solar zenith angle (Refs. 12 and 15). The coefficients associated with the linearized spatial sub-models are computed using (theoretical) IPP-derived signal amplitude characteristics for uniformly illuminated daytime and nighttime paths. The coefficients associated with the linearized diurnal sub-models are derived from a limited amount of observed (non-uniformly illuminated) daytime path data. The resulting semi-empirical model (Ref. 14) provides accurate and efficient signal amplitude predictions at any point in space and time where Mode 1 is the dominant mode of the received signal.

In the semi-empirical signal amplitude model, the vertical component of the electric field, S, expressed in dB relative to one microvolt per meter (dB/μV/m), is given by (Ref. 16)

---

*Signal attenuation rate and excitation factor as a function of various geophysical parameters.

$$S = C + 10 \log P - (10 \log h_t' + 10 \log h_r')$$

$$- 10 \log [a \sin (\frac{d}{a})] + \frac{1}{2} (\Lambda_t + \Lambda_r)$$

$$- \sum_{\ell=1}^{L} [(\alpha_\ell \; \Delta d_\ell)/10^6] \qquad (2.4\text{-}1)$$

where

C = Frequency-dependent constant

= 154.2 dB/μV/m for 10.2 kHz Omega signals

P = Effective radiated power (kW) = 10 kW

h_t' = Ionosphere reference reflection height at the transmitting station location (km)

h_r' = Ionosphere reference reflection height at the receiver location (km)

Λ_t = Signal excitation factor at the transmitting station (dB)

Λ_r = Signal excitation factor at the receiver location (dB)

a = Radius of earth (m)

d = Transmitting station-to-receiver path length (m)

$a \sin(d/a)$ = Geometric-spreading factor of the transmitted signal

L = Total number of segments comprising the path

Δd_ℓ = Length of the ℓ^{th} segment of the path (m)

α_ℓ = Signal attenuation rate (db/Mm) over ℓ^{th} path segment, Δd_ℓ

$\sum_{\ell=1}^{L} \frac{(\alpha_\ell \; \Delta d_\ell)}{10^6}$ = Total signal loss over the entire signal path (dB)

The signal amplitude equation, Eq. 2.4-1, includes two signal quantities: attenuation rate, α, and excitation factor,

Λ, of the signal propagating along the prediction path waveguide. These signal quantities are functions of spatially and diurnally varying geophysical path properties and hence they vary both spatially along a prediction path and diurnally at each point along the path.

The diurnal variations of α, Λ and h' are assumed to be given by the following solar zenith angle-dependent functions:

$$\alpha = [1 - \tau(\chi)]\ \alpha(D) + \tau(\chi)\ \alpha(N) \qquad (2.4\text{-}2)$$

$$\Lambda = [1 - \tau(\chi)]\ \Lambda(D) + \tau(\chi)\ \Lambda(N) \qquad (2.4\text{-}3)$$

$$\log h' = [1 - \tau(\chi)]\ \log h'(D) + \tau(\chi)\ \log h'(N) \qquad (2.4\text{-}4)$$

where χ is the solar zenith angle. The interpolation function, $\tau(\chi)$, is zero along a daytime path segment ($\chi \leq 74°$), is unity over a nighttime path segment ($\chi \geq 98°$), and along a transition path segment ($74° < \chi < 98°$) is given by

$$\tau(\chi) = \frac{1}{2}\left[1 - \cos\left(\frac{180\ (\chi-74)}{24}\right)\right] \qquad (2.4\text{-}5)$$

The designator D or N within the parentheses following the quantities α, Λ and h' in Eqs. 2.4-2 through 2.4-4 indicates that these quantities are evaluated for daytime or nighttime solar illumination along the path segment. The values of h'(D) and h'(N) are 70 km and 87 km, respectively. The expressions for $\alpha(D/N)$ and $\Lambda(D/N)$ are functions of spatial and diurnal geophysical parameters* of a signal path and are given in Table 2.4-1. Each modal quantity is a sum of geophysical functional forms, f_j, multiplied by appropriate weighting coefficients, K_j, given in Table 2.4-1. This model, along with the atmospheric noise

*α is computed for each individual segment comprising the path; while $\Lambda_{t/r}$ is the average value of Λ calculated over the 11 segments adjacent to the transmitter(t)/receiver(r).

TABLE 2.4-1

SIGNAL AMPLITUDE MODEL FUNCTIONAL FORMS AND WEIGHTING COEFFICIENTS (REF. 16)

T-3535a

SIGNAL QUANTITY EQUATION[1]	j	FUNCTIONAL FORM[2], f_j	WEIGHTING COEFFICIENT, K_j: DAYTIME[3] PATH	WEIGHTING COEFFICIENT, K_j: NIGHTTIME PATH
$\alpha(D/N) = \sum_{j=1}^{7} K_j f_j + \sum_{j=11}^{13} K_j f_j$ (dB/Mm)	1	$\sigma_g^{-0.66}$ if $\sigma_g > 10^{-5}$, otherwise 0.0	0.022	0.012
	2	1.0 if $\sigma_g = 10^{-5}$, otherwise 0.0	35.12	21.74
	3	1.0	3.19	1.07
	4	$\sin\beta_m \cos\theta_m$	-0.97	-0.82
	5	$(1 - \cos 2\beta_m)\cos\theta_m$	0.11	-0.08
	6	$\sin\beta_m \exp(-\theta_m^2/18^2)$ if $270° \geq \beta_m \geq 150°$, otherwise 0.0	0.0	-1.43
	7	$\exp[-(\beta_m-199)^2/31^2 - (\theta_m^2/18^2)]$ if $270° \geq \beta_m \geq 150°$, otherwise 0.0	0.0	5.61
	11	χ^2	0.62	0.0
	12	χ^4	-0.72	0.0
	13	χ^6	0.30	0.0
$A(D/N) = \sum_{j=8}^{10} K_j f_j$ (dB)	8	$\sigma_g^{-0.35}$	0.067	0.115
	9	1.0	0.3	-1.8
	10	$\exp(-\theta_m^2/20^2)\sin\beta_m$ if $\beta_m \geq 270°$, otherwise 0.0	0.0	12.9

Notes:

1 - D/N denotes day/night illumination along signal path

2 - σ_g = ground conductivity (mhos/m); χ = solar zenith angle (rad); θ_m = magnetic latitude (deg); β_m = magnetic bearing (deg). Because of functional form symmetry about β_m = 90° and 270°, forms are shown only for $90° \leq \beta_m \leq 270°$; for $0° \leq \beta_m < 90°$ and $270° < \beta_m \leq 360°$, replace β_m by $(180°-\beta_m)$ and $(540°-\beta_m)$, respectively.

3 - In the numerical fit to IPP, Daytime Path coefficients K_3, K_{11} K_{12} and K_{13} are 3.47, 0.0, 0.0, and 0.0, respectively.

amplitude prediction model (Section 2.4.2), is used to compute signal-to-noise ratio boundaries for the Omega signal coverage prediction diagrams.

2.4.2 Modal Interference Effects Model

The IPP model is used to predict the modal interference-induced phase deviations along daytime and nighttime signal paths in the coverage diagrams. For mixed paths in the coverage diagrams, a modal interference model which is based on limited empirical observations is used.

Daytime/Nighttime Paths - The severity of modal interference effects over a daytime or nighttime path can be quantified by the phase deviation, $\Delta\phi$. Consider the case where the signal propagating along a given path is composed of two strong-amplitude modes: Mode 1 (the desired mode) and Mode 2 (the interfering mode). The total signal at any point along a propagation path is a vector sum (including phase angle) of the fields of Modes 1 and 2.* For example, the vertical component of the electric field, E, of the resultant (i.e., total) signal propagating along the path is

$$E = \sum_{m=1}^{2} E_m \qquad (2.4\text{-}6)$$

where E_m is the vertical component of the electric field of the m^{th} mode. Figure 2.4-1 depicts a phasor sum of the vertical component of the electric field of the two modes described by phasors E_1 and E_2 in Eq. 2.4-6. In Fig. 2.4-1, it is assumed that the magnitude of E_1 is greater than the magnitude of E_2 and that E_2 has a phase angle, θ, which is defined with respect

*If more than two strong-amplitude modes exist, Mode 2 is the vector sum of all modes except Mode 1.

to E_1. The amplitude, $|E|$, and phase angle relative to E_1, $\Delta\phi$, of the resultant electric field, E, are then given by

$$|E| = \left[|E_1|^2 + |E_2|^2 + 2|E_1||E_2| \cos\theta\right]^{1/2} \qquad (2.4\text{-}7)$$

$$\Delta\phi = \tan^{-1}\left[\frac{\sin\theta}{(|E_1|/|E_2|) + \cos\theta}\right] \qquad (2.4\text{-}8)$$

For station signal coverage prediction paths in daytime or nighttime, the phase deviations are computed using Eq. 2.4-8 where the amplitude and phase of the component modes forming the total signal are obtained from the theoretical IPP model (Ref. 4).

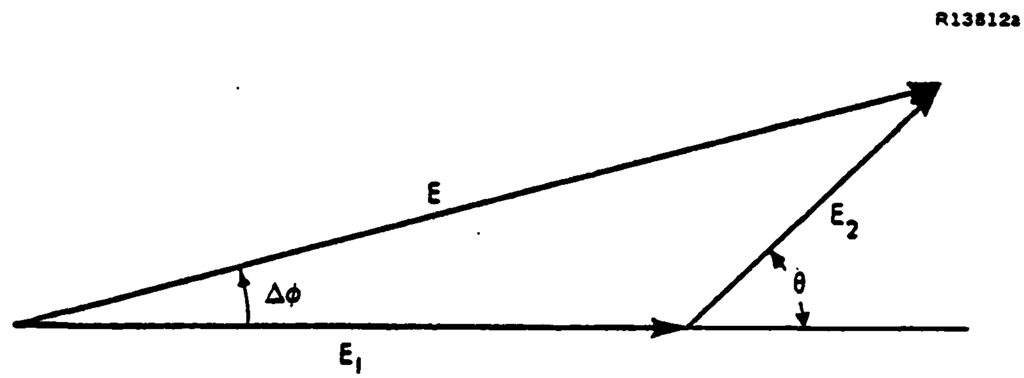


Figure 2.4-1   Phasor Summation of Two Modes

<u>Mixed Path</u> - For station signal coverage prediction paths under mixed illumination, a simple algorithm is used to determine if excessive modal interference effects are expected at the coverage prediction point. Based on observations of Liberia and Argentina station 10.2 kHz signals, severe "nighttime-type" modal interference effects do not generally occur on mixed paths which are more than two-thirds in daytime. Exceptions have been noted, of course, but this observation provides a reasonable basis for developing an algorithm to estimate mixed

path modal interference effects. The algorithm proceeds by first noting whether the mixed path coverage prediction point in question would be subjected to excessive modal interference effects (i.e., $\Delta\phi > 20$ cec) if the entire prediction path were under nighttime illumination. This is done by employing Eq. 2.4-8 with the amplitude and phase of component modes obtained from IPP. If the nighttime interference effects are estimated to be excessive at the prediction point, and if the nighttime portion of the path is more than one-third of the total path length, the prediction point is assumed to have excessive mixed path modal interference effects.

2.4.3 Atmospheric Noise Amplitude Prediction Model

Electromagnetic atmospheric noise in the very low frequency range is generated mainly by lightning discharges associated with thunderstorms. The amplitude of this noise at any particular receiver location on the surface of the earth is the combination of electromagnetic fields radiated by these thunderstorms. The best-known noise amplitude prediction model* is the model described in CCIR Report 322 (Ref. 16) in which global noise measurement data are fit with smooth curves as functions of latitude, longitude, time of day, season of the year, and frequency. Another approach to the problem of VLF noise field predictions has been carried out by Maxwell (Ref. 17) and modified by the U.S. Naval Research Laboratory (NRL). This modified model, known as the Westinghouse/NRL model, is believed to represent an improvement over the CCIR model and is used to develop the new signal coverage prediction diagrams. The computer program implementation of the modified model is given in Ref. 18.

---

*The currently available Omega signal prediction diagrams are based on the CCIR noise amplitude prediction model.

2.5 GEOMETRIC DILUTION OF PRECISION

A position fix can be obtained by the intersection of two hyperbolic lines-of-position (LOPs), each of which may be in error. Figure 2.5-1 shows the intersection of two such LOPs derived from three Omega stations. Geometric Dilution Of Precision (GDOP) is a measure of the sensitivity of position fix accuracy to errors in phase difference measurements, usually expressed in kilometers per cycle. As GDOP increases in a given area, the impact of measurement noise and propagation vagaries increases. GDOP is affected by both the spreading of hyperbolic lines and the crossing angle between LOPs (see Fig. 2.5-1).

The first-order position fix error, assuming the phase error standard deviation is the same for both LOPs, may be expressed by (Ref. 19)

$$\sigma_r = \frac{\lambda\, \sigma_\phi}{2 \sin\theta}\left[\csc^2\left(\frac{\phi_{12}}{2}\right) + 2\rho \cos\theta \csc\left(\frac{\phi_{12}}{2}\right)\csc\left(\frac{\phi_{13}}{2}\right) + \csc^2\left(\frac{\phi_{13}}{2}\right)\right]^{1/2} \tag{2.5-1}$$

where

λ = Signal wavelength (km)

σ_r = Standard deviation of radial error (km)

σ_ϕ = Standard deviation of LOP phase error (cycles)

ϕ_{12} = Angle subtended at receiver by transmitting stations 1 and 2

ϕ_{13} = Angle subtended at receiver by transmitting stations 1 and 3

θ = Crossing angle between LOP_{12} and LOP_{13}

ρ = Phase error correlation between LOP_{12} and LOP_{13} = 0.5.

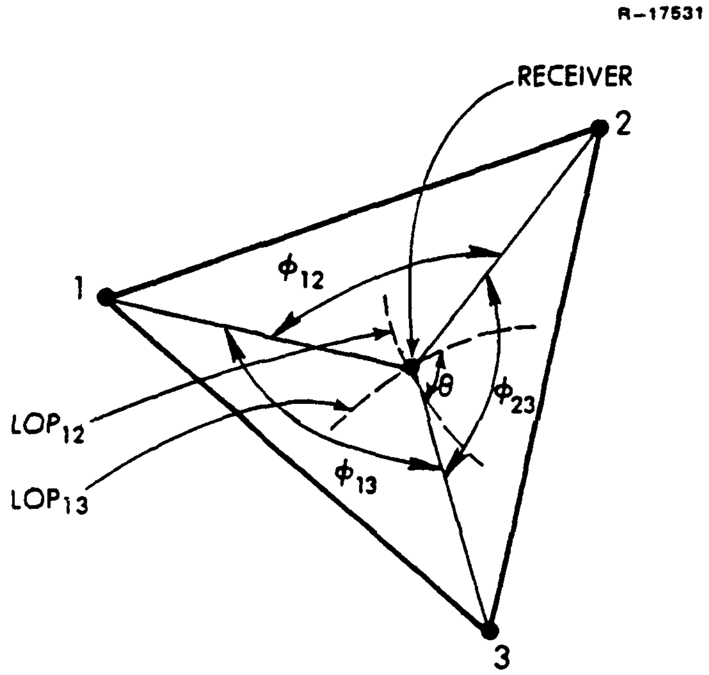


Figure 2.5-1   Position Fix Geometry Between Receiver and Transmitting Stations 1, 2 and 3

GDOP, the ratio of radial error, σ_r, to the LOP phase error, σ_ϕ, is then given by

$$\mathrm{GDOP} = \frac{\sigma_r}{\sigma_\phi}\ \text{(km/cycle)} \qquad (2.5\text{-}2)$$

where σ_r is given by Eq. 2.5-1. Equation 2.5-2 is used to identify areas in the three and four usable signal regions in a composite coverage diagram where GDOP exceeds the prescribed threshold value of one kilometer per centicycle (0.01 cycle) for all of the available station combinations.

3. SIGNAL COVERAGE AND NIGHTTIME MODAL INTERFERENCE DIAGRAMS

The methodology employed to prepare the individual Omega station signal coverage diagrams, individual station nighttime modal interference diagrams, and composite signal coverage diagrams is presented in this chapter. Nighttime modal interference diagrams display regions where modal interference-induced phase deviations in a station signal propagating under assumed nighttime propagation conditions are predicted to be less than or equal to the threshold value of 20 cec. An individual station signal coverage diagram shows the predicted global accessibility of usable signals from the station at a selected time for both signal access criteria. A composite diagram displays the predicted global accessibility of usable signals from the Omega Navigation System at a selected time and a selected signal access criterion. Sample diagrams of individual station nighttime modal interference, individual station coverage, and composite signal coverage are given in this chapter. The complete set of interference diagrams are provided in Appendix A of this volume. Individual station coverage diagrams are contained in Volume II, and composite diagrams are contained in Volume III.

3.1 USABLE SIGNAL ACCESS CRITERIA

A station signal at a specific point on the earth at a given time is considered usable if the signal satisfies the following usable signal access criteria (specified by ONSOD):

- The predicted signal-to-noise ratio (SNR) in the 100 Hz receiver noise bandwidth is greater than or equal to the prescribed threshold value of:

  SNR Criterion 1: -20 dB

  SNR Criterion 2: -30 dB

- The predicted deviation in the total signal phase due to modal interference effects, $\Delta\phi$, is less than or equal to 20 centicycles over an extended path segment (i.e., longer than one megameter) through the point

- The signal propagation is along the short path from the station.

Signal behavior in the vicinity of a station antipode* is quite complex because of geometrical convergence and also because of possible antipodal signal interference between the direct (short-path) and wrong-way (long-path) signals. Signals affected by antipodal interference are considered to be unusable for navigation. Therefore, in the coverage diagrams, the unusable short-path signals at distances greater than 19 megameters from a transmitting station and the long-path (at distances greater than 20 megameters) signals are assumed to be unusable.

In the "near-field" region of a transmitting station (distances of up to 500 km from the station), complex Omega signal behavior results in significant modal interference effects. Therefore, $\Delta\phi$ is not computed in the near-field region of a station but is assumed to be greater than 20 cec.

*The station antipode is the point on the earth's surface which diametrically opposite to the transmitting station.

3.2 SIGNAL COVERAGE AND MODAL INTERFERENCE CALCULATIONS

3.2.1 Signal-to-Noise Ratio Contours

A contour of constant signal-to-noise ratio is the locus of points where the signal-to-noise ratio of a transmitting station signal is a specified threshold value for a given prediction time. The signal-to-noise ratio is greater than the threshold level on one side of the contour (toward the station) and is less than the threshold level on the other side of the contour (away from the station). The -20 dB and -30 dB signal-to-noise ratio contours are obtained for each Omega station at 10.2 kHz for the eight selected coverage times. The receiver noise bandwidth is assumed to be 100 Hz and the transmitter radiated power is taken to be 10 kW for all signal-to-noise ratio computations.

Signal-to-noise ratio contours are computed by a modified version of Program CONTOUR (Ref. 20) using signal amplitude data generated by the semi-empirical model described in Section 2.4 and the atmospheric noise field data computed using the Westinghouse/NRL noise model (Ref. 18). For each of the selected eight coverage times, the -20 dB and -30 dB signal-to-noise ratio points of a transmitting station signal are determined along each of 30 to 40 great-circle radial propagation paths emanating from the station. These radial paths are chosen to adequately describe the changing geophysical propagation properties of the world from each station. Beginning from a north-directed radial, radial paths are launched at an angular spacing of 15°, with additional radial paths through both the Greenland and Antarctic regions to provide a 5° spacing between radials through these regions. Also, radial paths are added, as necessary, to adequately define large variations occurring in the signal-to-noise contour boundaries. These variations are caused by a combination of both the rapidly changing conductivity of local land masses and the relative lengths of the radial path segments through these regions.

Starting at a transmitting station, signal-to-noise ratio is computed and compared against the threshold value of -20 dB at each of the successive computation points (spaced at approximately 60 km intervals) along a radial path. This procedure is continued along each radial until either a point with -20 dB signal-to-noise ratio is reached or the distance between the computation point and the station exceeds 19 Mm. Because of possible antipodal interference, signals beyond 19 Mm from the station are assumed to be unusable and hence the signal-to-noise ratios at these distances are assumed to be less than the threshold value. A similar procedure is followed to determine the predicted -30 dB signal-to-noise ratio contour boundary. Each of these predicted contours is adjusted to reflect available reliable observations provided by ONSOD. These adjusted contours are then used to construct the final station signal coverage prediction diagrams described in Section 3.3.

3.2.2 Modal Interference-Free Zone Boundaries

A modal interference-free zone boundary (or boundaries) of a transmitting station is the locus of points surrounding the zone (or zones) within which the modal interference-induced phase deviations in the station signal are less than or equal to the threshold value of 20 cec. For each station, theory-based modal interference-free zone boundaries are first determined for both daytime and nighttime propagation conditions along signal paths. For each station, the phase of both the Mode 1 signal and the deviation of the total signal phase from the Mode 1 signal phase are computed by the modal interference model (described in Section 2.3) at each successive computation point (spaced at approximately 100 km intervals) along each of the several great-circle radial paths. These radial paths are launched at 45° intervals at a station with additional radials interspersed as necessary for adequate definition of the zone boundary (or boundaries). The phase deviation, $\Delta\phi$, along each radial path is then examined

by the modified version of Program CONTOUR (Ref. 23) to determine the location of extended path segments which are at least one megameter long and have deviation less than or equal to 20 cec. These extended path segments of a station form its modal interference-free zone (or zones). This $\Delta\phi$ computation procedure is continued along each station radial path up to 19 Mm from the station. Because of possible antipodal interference, signals beyond 19 Mm from the station are assumed to be unusable and hence $\Delta\phi$ beyond 19 Mm is assumed to be greater than the threshold value. The model-based modal interference-free zone boundaries of each Omega station are then adjusted to reflect available reliable observations provided by ONSOD. The modified daytime and nighttime boundaries are then used in the mixed path modal interference algorithm (given in Section 2.3) to generate mixed path modal interference boundaries at the various selected coverage times. These boundaries are used to construct the final coverage diagrams described in Section 3.3.

An example of the predicted nighttime modal interference-free zone boundaries for the Hawaii station at 10.2 kHz is shown in Fig. 3.2-1. The solid line describing a zone boundary corresponds to theoretical $\Delta\phi$ predictions actually computed. The dotted line extends the boundary and shows the extrapolation of the boundary beyond the limit of computed predictions. In Fig. 3.2-1, the modal interference-free zone (i.e., $\Delta\phi \leq 20$ cec) begins at the zone boundary and extends in the direction of the arrows shown in the figure. Note that the modal interference boundary for the Hawaii station persists to rather long distances along east- and west-directed paths. Nighttime modal interference diagrams for each of the eight Omega stations at 10.2 kHz are given in Appendix A.

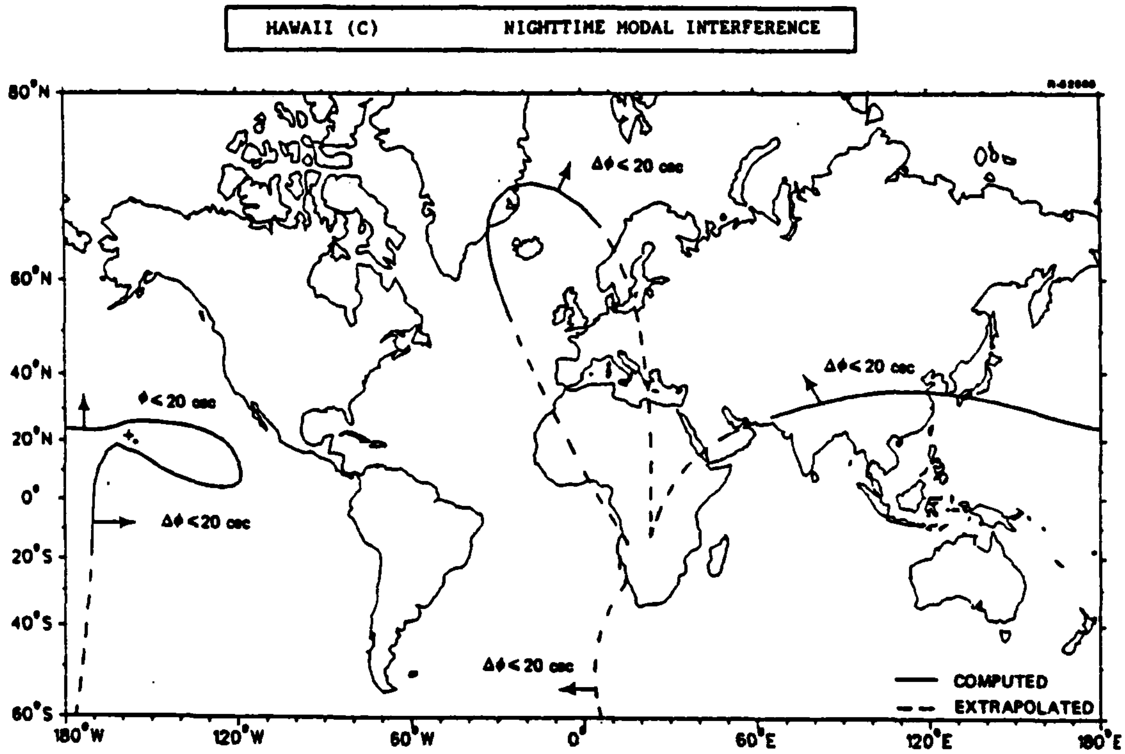


Figure 3.2-1 Modal Interference Diagram for the Hawaii (C) Station at 10.2 kHz

3.3 INDIVIDUAL STATION SIGNAL COVERAGE PREDICTION DIAGRAMS

Individual Omega station signal coverage prediction diagrams are prepared in a Mercator projection for each of the eight coverage times selected in Section 2.2. This projection is centered at 0° longitude and shows coverage between latitudes of 60° S and 80° N. Each station prediction diagram is plotted by Program CONTOUR and displays

- Both the -20 dB and -30 dB SNR contours
- The 20 cec Δφ boundaries at the selected coverage time.

An example of an individual station coverage prediction diagram for the Norway station is shown in Fig. 3.3-1. The SNR contours in the diagram are drawn as solid lines and the $\Delta\phi$ contour is shown as a dashed line. In each diagram, the SNR is above (or $\Delta\phi$ is below) the threshold level on the side of the contour in the direction of the arrow. For example, north of Rio de Janerio, the Norway station SNR coverage at August 1800 GMT is shown to be greater than -30 dB, while south of Rio de Janerio, the Norway SNR coverage is predicted to be less than -30 dB. The phase deviation of Norway signals (see Fig. 3.3-1) in and around Brazil are shown to be less than 20 cec. For all coverage diagrams in this study, the receiver noise bandwidth is assumed to be 100 Hz and the power radiated from each station is taken to be 10 kW. The usable signal coverage regions of a station are the regions where both the SNR and $\Delta\phi$ threshold criteria are satisfied. For example, near the Norway station within the dotted contour (see Fig. 3.3-1), Norway signals are unusable (based on either signal access criterion) as the phase deviation is predicted to be greater than the threshold level of 20 cec even though the SNR at this point is predicted to be greater than both SNR criterion threshold values.

The individual station signal coverage prediction diagrams developed in this study and presented in Volume II of this report (Ref. 4) reveal that

- The largest regions of severe signal phase deviation (due to modal interference effects) are associated with low-latitude Omega transmitting stations
- The usable signal coverage of a station extends to shorter distances along an illuminated (daytime) path than along a non-illuminated (nighttime) path due to the relatively higher signal attenuation rate along a daytime path

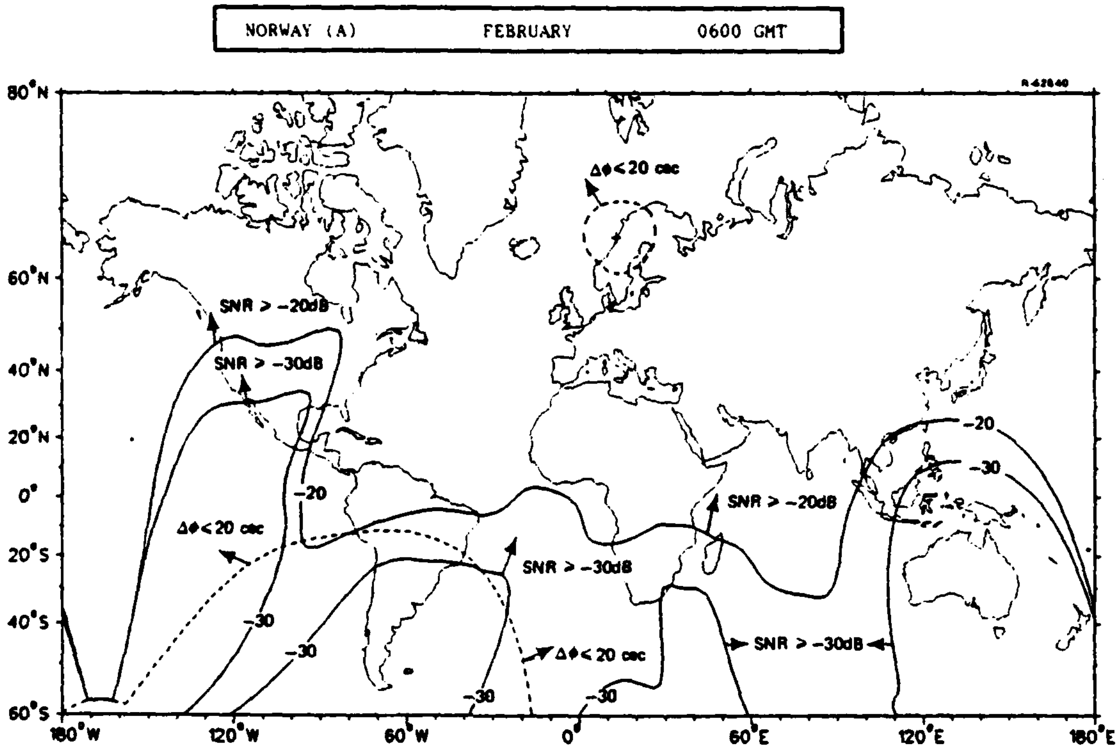


Figure 3.3-1 Individual Station 10.2 kHz Signal Coverage Diagram for the Norway (A) Station: February, 1800 GMT

- Usable signal coverage of a station generally extends to relatively

  long distances in the easterly direction

  short distances in the westerly direction

  moderate distances in the northerly/southerly directions

  due to anisotropic signal attenuation rate (and phase) behavior induced by the geomagnetic field

- Usable signal coverage extends to shorter distances in Greenland and Antarctica due to very low conductivity and thus extremely high (both daytime and nighttime) signal attenuation rate

- Signal access Criterion II (i.e., SNR $\geq$ -30 dB) boundaries may extend by as much as 10 Mm from the Criterion I (i.e., SNR $\geq$ -20 dB) boundaries.

The individual station diagrams for a given coverage time are combined to produce a composite diagram as described in Section 3.4.

3.4 COMPOSITE SIGNAL COVERAGE PREDICTION DIAGRAMS

A composite signal coverage diagram displays the predicted global accessibility of usable 10.2 kHz signals from the Omega Navigation System at a given time for a prescribed signal access criterion. A composite diagram for a given time and signal access criterion is constructed by overlaying the appropriate individual station signal access contours. The signal access boundary of a station is the set of boundary curves within which both the SNR and $\Delta\phi$ criteria are satisfied while outside of the boundary one or both criteria are not satisfied.

For effective display of Omega coverage at both high- and low-latitude regions of the world, separate coverage diagrams are constructed for

- Both low- and mid-latitudes regions (between 60° South and 80° North) with a Mercator projection of the world
- North and South polar regions between North (or South) pole and 55° North (or South) latitude with an Azimuthal Equal Distance (AED) projection of the world.

A total of 48 composite coverage diagrams (8 coverage times × 2 signal access criteria × 3 projections) are constructed for the Omega Navigation System and are contained in Volume III of this report. Examples of the three projections of the

composite coverage at February 1800 GMT are shown in Figs. 3.4-1 through 3.4-3. In a composite coverage diagram, the combination of signals that can be accessed in a region is indicated by the set of letters within the contours enclosing the region. For example, in the composite diagram shown in Fig. 3.4-1, it can be seen that the expected coverage in Iceland is from stations A, B, D, F and H. Some regions display a number indicating the number of signals that can be received in that region. The corresponding stations, however, can be readily determined as each coverage contour is labeled with a station designator and an arrow in the direction of the availability of the usable signal from the labeled station. For example, the region around the Norway station is labeled with a number 6. It is readily seen that coverage in this region is from stations B, C, D, E, F and H. The coverage diagrams also indicate (with shading) areas where the geometric dilution of precision (GDOP) exceeds a prescribed threshold value. In the shaded areas of the diagrams, all usable station signal combinations yield a GDOP above the prescribed threshold value of one kilometer of radial position error per centicycle of LOP phase error. The position fix error in these shaded areas is expected to be much larger than in the non-shaded areas having three or more usable signals.

The composite coverages for the eight selected coverage times (presented in Volume III of this report) are quantified in Table 3.4-1 as the coverages associated with various usable signal station combinations for various times and signal access criteria. The table shows that the Omega signal coverage is worldwide: over 95 percent of the earth's surface is covered at all times by at least three Omega station signals (with good geometry) that can be utilized by a user employing a medium-performance (i.e., signal access Criterion I) receiver. For the same receiver, over 84 percent of the earth's surface is covered by at least four station signals (with good geometry) which provides one station redundancy for off-air periods. Furthermore,

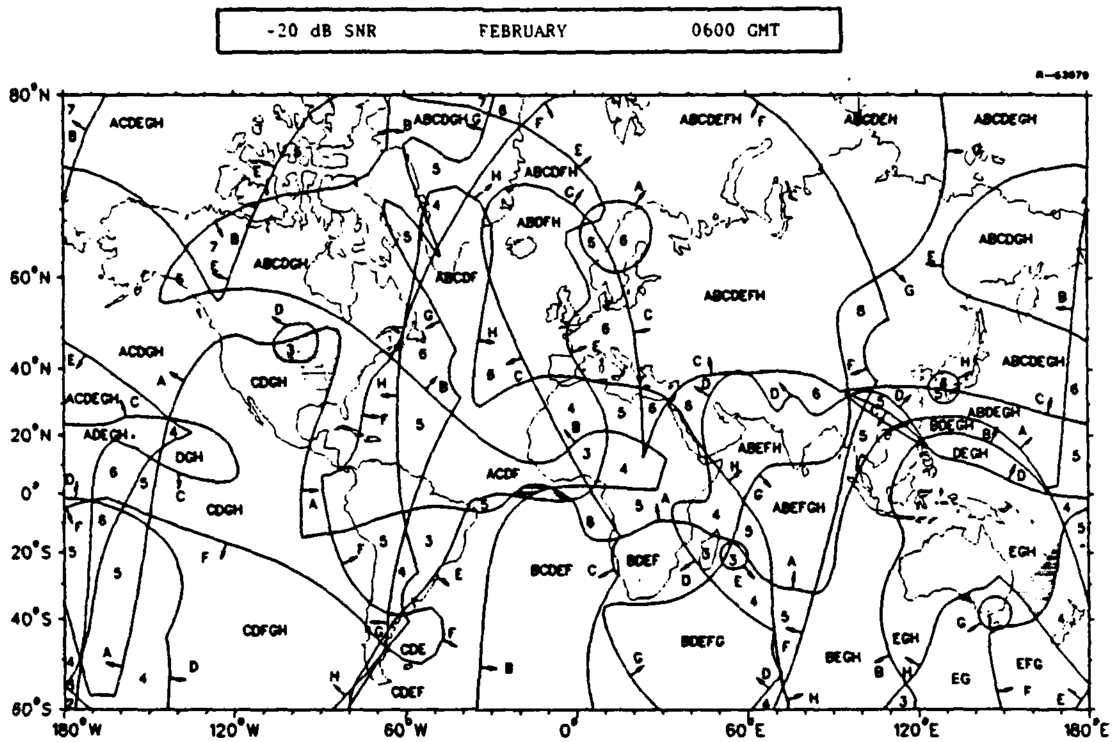


Figure 3.4-1 Composite 10.2 kHz Signal Coverage Prediction Diagram at February 0600 GMT Based on Signal Access Criterion I--Mercator Projection

TABLE 3.4-1

COMPOSITE SIGNAL COVERAGE

T-4488

NUMBER OF USABLE SIGNAL STATIONS	SIGNAL ACCESS CRITERION	PERCENTAGE OF THE EARTH'S SURFACE COVERED (EXCLUDING POOR GEOMETRY* AREAS)							
		TIME							
		0600 GMT				1800 GMT			
		FEBRUARY	MAY	AUGUST	NOVEMBER	FEBRUARY	MAY	AUGUST	NOVEMBER
3	I	11	8	8	9	8	11	11	9
	II	4	1	<1	2	<1	1	<1	<1
3 or more	I	95	96	97	96	95	97	97	96
	II	99	99	99	99	99	99	99	99
4 or more	I	84	88	89	87	87	86	85	87
	II	94	98	98	97	99	98	98	98

*GDOP > 1 km/cec.

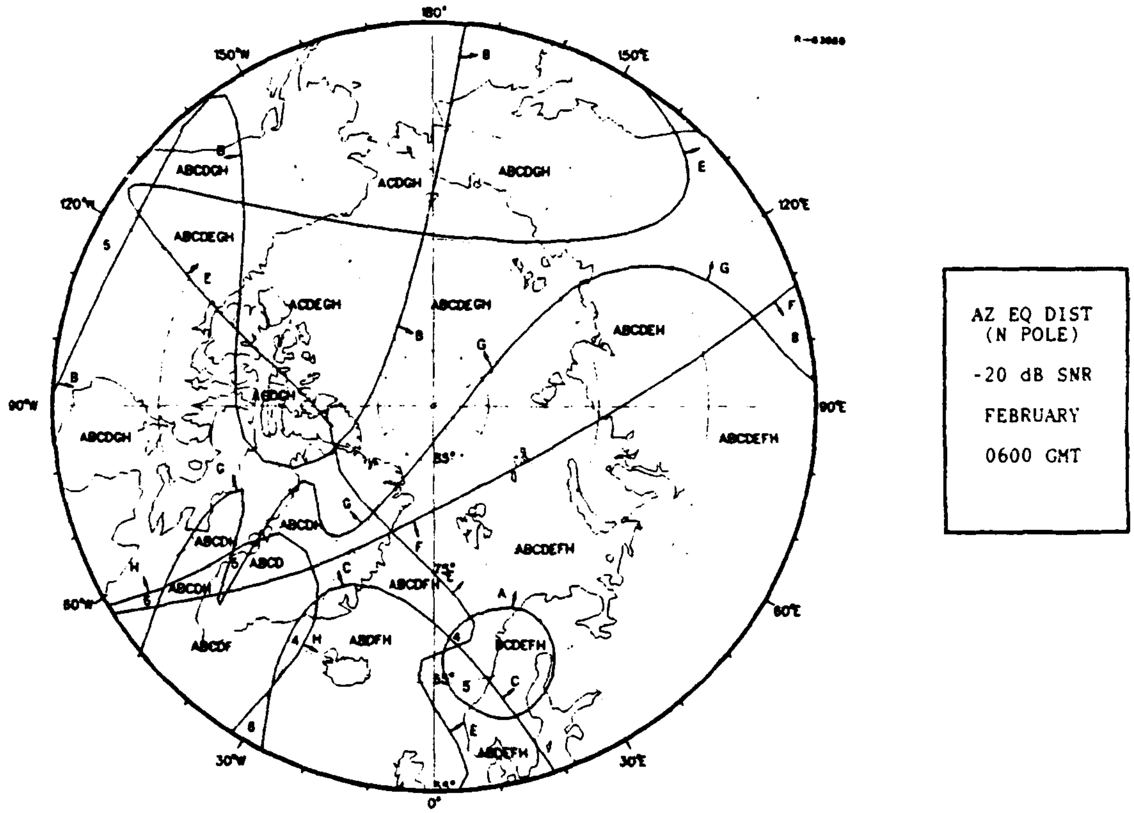


Figure 3.4-2 Composite 10.2 kHz Signal Coverage Prediction Diagram at February 0600 GMT Based on Signal Access Criterion I--Azimuthal Equal Distance Projection Centered at North Pole

these coverages increase to 99 percent for a user employing a higher-performance (i.e., signal access Criterion II) receiver. Variations in the composite Omega signal coverage (see Table 3.4-1) with either GMT or month are small.

3.5 SIGNAL COVERAGE AVAILABILITY

The station signal coverage prediction diagrams are strictly valid only for those conditions specified by the

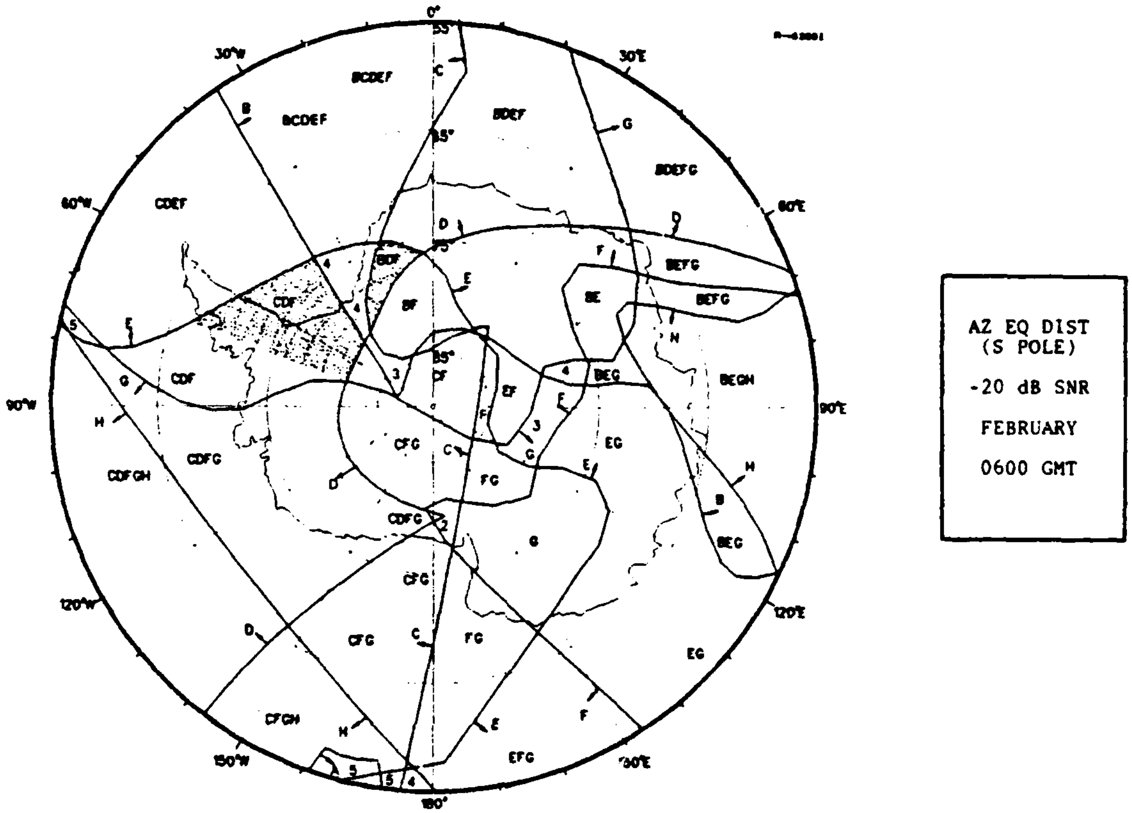


Figure 3.4-3 Composite 10.2 kHz Signal Coverage Prediction Diagram at February 0600 GMT Based on Signal Access Criteria I--Azimuthal Equal Distance Projection Centered at South Pole

assumed signal access criterion -- e.g., 10.2 kHz signal from the Norway station, 0600 GMT in February, SNR (100 Hz bandwidth) $\geq$ -20 dB, and $\Delta\phi \leq$ 20 cec. The signal coverage diagrams developed herein display signal coverages for a representative cross-section of governing conditions. Therefore, these diagrams can be employed by a user to assess coverage at conditions other than those employed in the diagrams. However, caution must be exercised in performing interpolation of the signal coverage prediction diagrams. For example, coverage at GMTs differing by at most one hour from the stated GMT will

generally be approximately the same as the indicated coverage at the stated GMT, but global coverage patterns at GMTs four to six hours from either of the GMTs at 12-hr intervals may, in many cases, differ substantially from coverage at the stated GMT.

A user interested in coverage over a small area should note that if the area is to be crossed by a day/night terminator within a few hours, coverage during that period is likely to be transitory and not reliably predicted. Except in the high-latitude regions, the solar zenith angle at a given GMT changes less over three months than over 12 hours in a given month. Therefore, any point can be interpolated more reliably between months than between GMTs.

Spatial interpolation of coverage contours, e.g., identifying the location of a -25 dB SNR contour or estimating the SNR at a particular point must be performed with care. For example, if a SNR contour is near a region of low conductivity or high local noise, large SNR gradients will be encountered and linear interpolation may be inaccurate. On the other hand, if the -20 dB and -30 dB contours are separated by approximately three-to-five megameters of relatively homogeneous ground and ionospheric parameters (relatively constant ground conductivity; not including terminator, geomagnetic pole or equator), interpolation may be performed with confidence.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 SUMMARY AND CONCLUSIONS

New Omega signal coverage prediction diagrams, developed and presented herein, display the predicted global availability of "usable" signals based on two usable signal access criteria:

Criterion 1

- Signal-to-noise ratio (SNR) $\geq$ -20 dB (in a 100 Hz noise bandwidth)
- Modal interference-induced deviation in signal phase, $\Delta\phi$, $\leq$ 20 centicycles

Criterion 2

- SNR $\geq$ - 30 dB (in a 100 Hz noise bandwidth)
- $\Delta\phi \leq$ 20 centicycles.

Eight times (0600 and 1800 GMT February, May, August and November) have been chosen to provide a representative cross-section of temporal signal behavior. The minimum station-terminator distance exceeds 700 km for all of the selected times.

Regions of usable signals are indicated on each diagram by the intersection of coverage boundaries for the SNR threshold and the modal interference-induced phase deviation threshold. The former is computed using a semi-empirical signal amplitude model presented in this report and the Westinghouse/NRL noise model (Ref. 18). The modal interference-induced phase deviation threshold boundaries are computed using the IPP model

(Ref. 4) along with the mixed path algorithm presented in this report. The computed SNR and $\Delta\phi$ contours of each station are modified to reflect available reliable observations provided by ONSOD. The modified contours are then combined to generate composite coverage diagrams of the Omega Navigation System at each of the eight selected times for each of two prescribed signal access criteria. Table 4.1-1 summarizes the salient characteristics of both new and existing (Ref. 3) coverage diagrams. From this table, it is evident that the new diagrams display the expected coverage over the entire diurnal and seasonal cycles of the year, as compared to the existing diagrams which provide the minimum and maximum bounds of the expected coverage. Individual station and composite coverage diagrams are bound separately in Volumes II and III, respectively. In addition, the bearing angles of great circles to the stations for a uniform latitude/longitude grid are tabulated in Volume IV.

TABLE 4.1-1

CHARACTERISTICS OF EXISTING AND NEW COVERAGE DIAGRAMS

T-4580

COVERAGE DIAGRAMS	SIGNAL MODEL	COVERAGE TIMES	SIGNAL ACCESS CRITERION		DIAGRAM PROJECTIONS†
			SNR (100 Hz BW)	$\Delta\phi$*	
EXISTING	THEORETICAL	TWO LOCAL TIMES: SUMMER NOON WINTER MIDNIGHT	$\geq$ -20 dB	$\leq$ 13 cec	MERCATOR
NEW	THEORETICAL AND DATA	8 GLOBAL TIMES: 0600 & 1800 GMT IN MID-FEB, MAY, AUG, & NOV	$\geq$ -20 dB & $\geq$ -30 dB	$\leq$ 20 cec	MERCATOR & AED (North & South)

*20 cec is currently considered by ONSOD to be a realistic threshold value for the modal interference-induced phase deviations, $\Delta\phi$.

†AED is Azimuthal Equal Distance Projection centered at the North or South Pole

Based on the new coverage diagrams presented here, it is concluded that even with the exclusion of (a) low-SNR signals, (b) signals with excessive modal interference-induced phase deviation, and (c) combinations of signals with high GDOP, the Omega Navigation System provides worldwide (in excess of 95 percent of the earth's surface) 10.2 kHz signal composite cov-erage (accessibility of three of more station signals) at all times. For those few regions not well covered by 10.2 kHz signals, it is conjectured that the higher Omega frequencies such as 13.6 kHz may provide useful supplementary signals.

4.2 RECOMMENDATIONS

The predictions diagrams presented here show 10.2 kHz Omega signal coverage (accessibility of 3 or more usable signals) to be worldwide (i.e., 95 percent of the world covered at almost all times). However, there are certain strategic navigational regions of the world (e.g., certain parts of the United States) where the number of available usable 10.2 kHz signals is three (no redundancy in case of a usable signal station outage) or less. In these regions, the use of 13.6 kHz signals along with 10.2 kHz signals is highly desirable to increase system reliability and to provide an accurate position fix capability. Also, most airborne receivers employ a combination of 10.2 and 13.6 kHz signals to obtain a position fix. Consequently, it is recommended that coverage diagrams (similar to coverage diagrams at 10.2 kHz) be developed for predicting global accessibility of usable 13.6 kHz signals.

APPENDIX A

NIGHTTIME MODAL INTERFERENCE DIAGRAMS

This appendix presents eight individual Omega station nighttime modal interference diagrams for 10.2 kHz. Diagram development methodology is described in Section 3.2. Table A-1 gives the key to these diagrams. Each diagram* displays the boundaries of theoretically-predicted (computed and extrapolated) modal interference-free zones of a station under assumed nighttime propagation conditions for the entire world. A zone boundary is the locus of points surrounding a zone within which $\Delta\phi \leq 20$ cec, where $\Delta\phi$ is the modal interference-induced phase deviation from the reference signal phase.

TABLE A-1

KEY TO NIGHTTIME MODAL INTERFERENCE DIAGRAMS

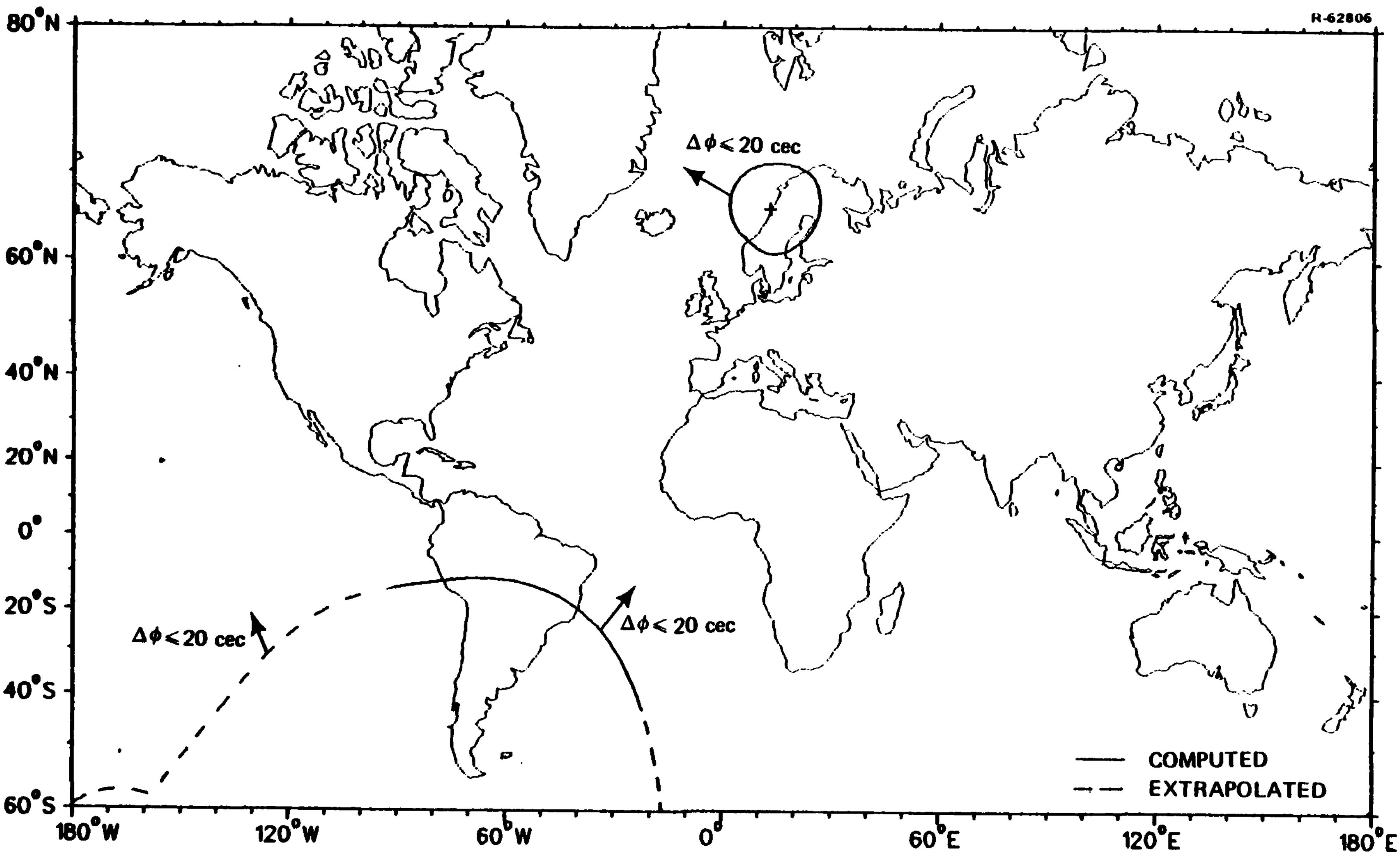
STATION	PAGE NO.
NORWAY	A-3
LIBERIA	A-4
HAWAII	A-5
NORTH DAKOTA	A-6
LA REUNION	A-7
ARGENTINA	A-8
AUSTRALIA	A-9
JAPAN	A-10

*All diagrams, except for the La Reunion station diagram, display the theoretically-predicted (Ref. 7) modal interference boundaries. The theoretically-predicted La Reunion station boundaries have been modified to reflect empirical observations provided by Omega Navigation System Operations Detail.

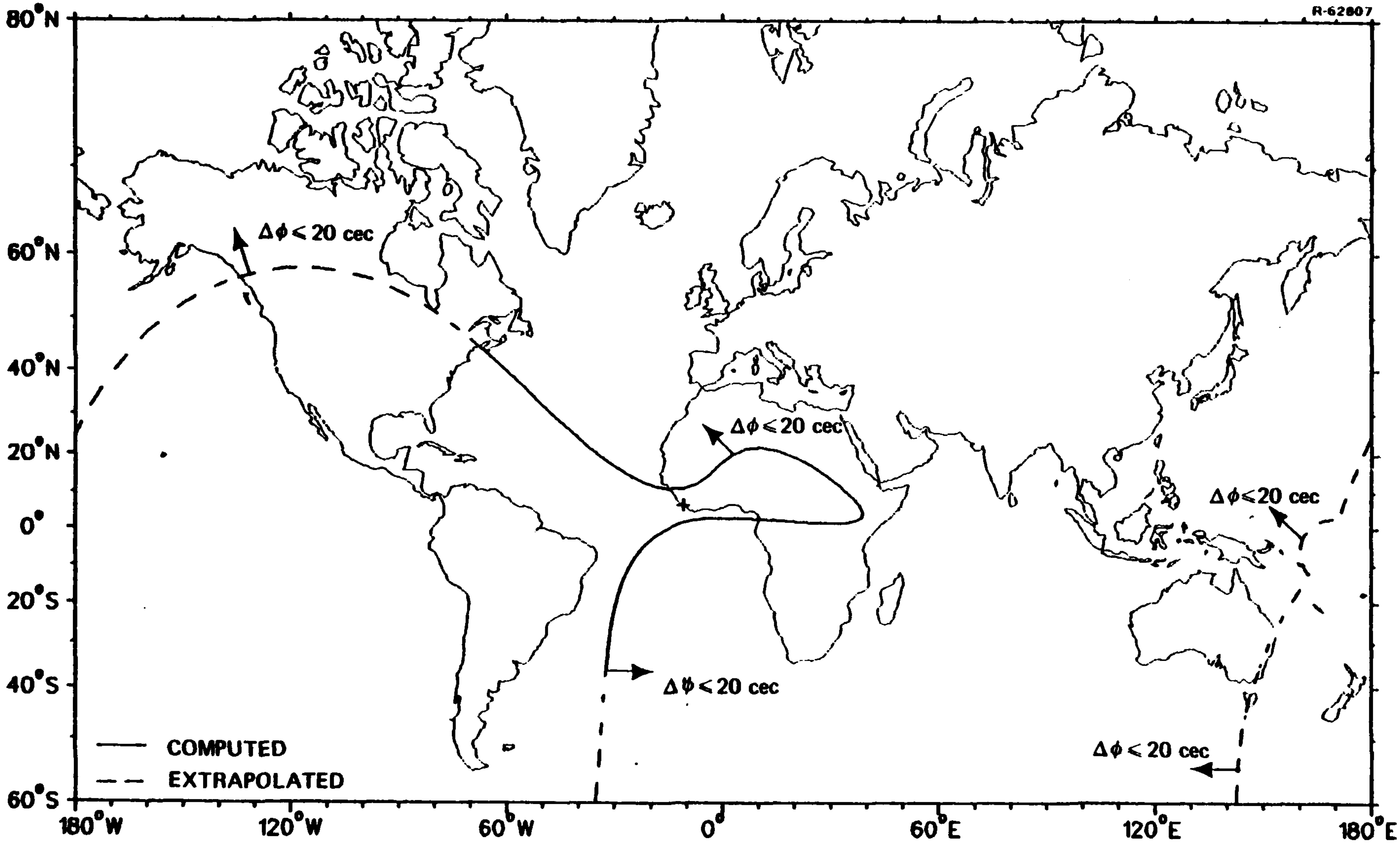
Because of possible interference between short-path and long-path signals in the vicinity of a transmitting station antipode, all signals beyond 19 Mm from the station have been assumed to be unusable for reliable navigation. Hence, regions beyond 19 Mm from a station have been excluded from the modal interference-free boundaries of the station.

In the modal interference diagrams, the solid line describes a zone boundary corresponding to the computed theoretical phase deviation predictions. The dotted line extends the boundary and shows the extrapolation of this boundary beyond the limit of computed projections. In these diagrams, the interference-free zone (i.e., $\Delta\phi \leq 20$ cec) begins at the zone boundaries and extends in the direction of the arrows as shown in these figures.

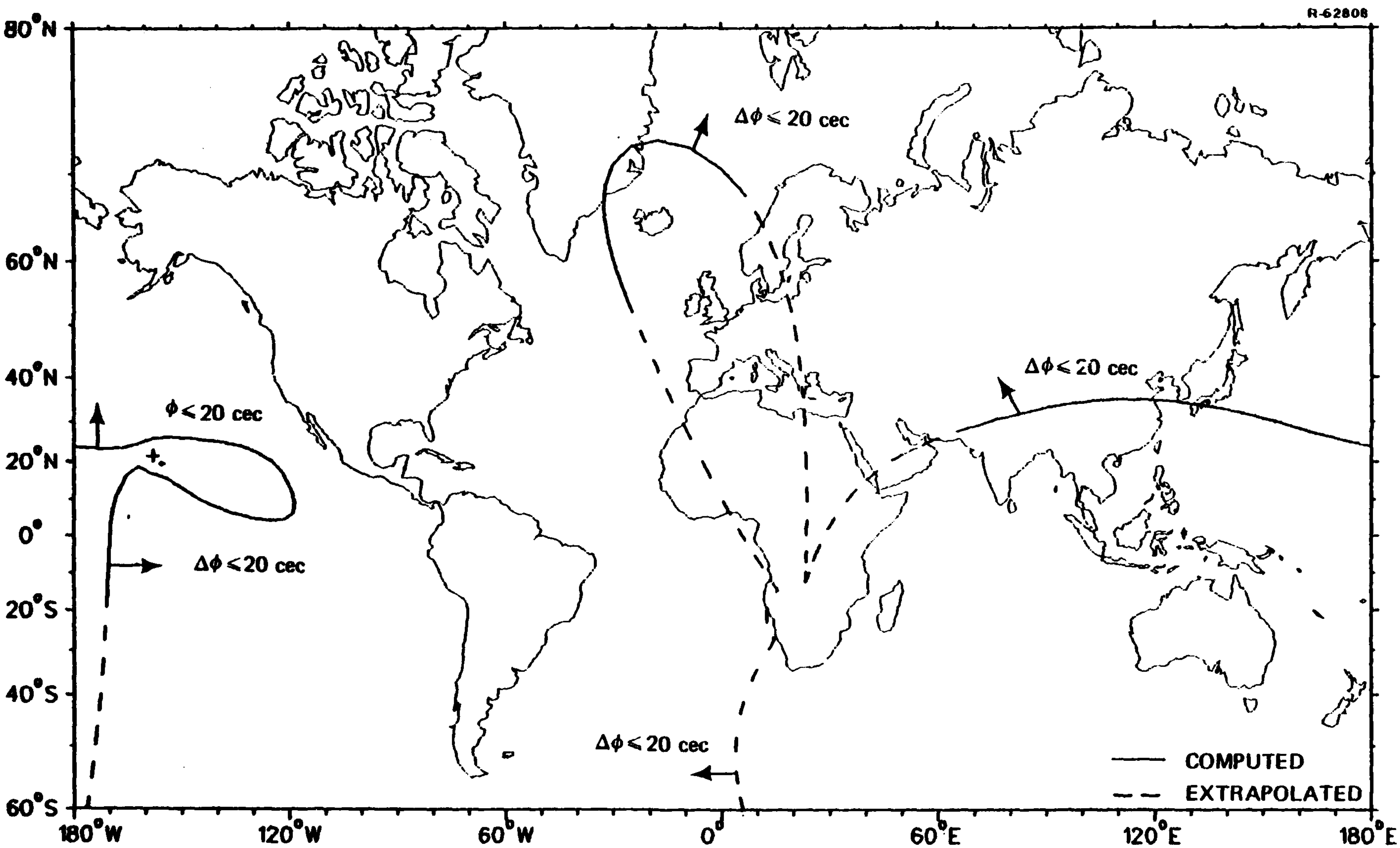
NORWAY (A) NIGHTTIME MODAL INTERFERENCE



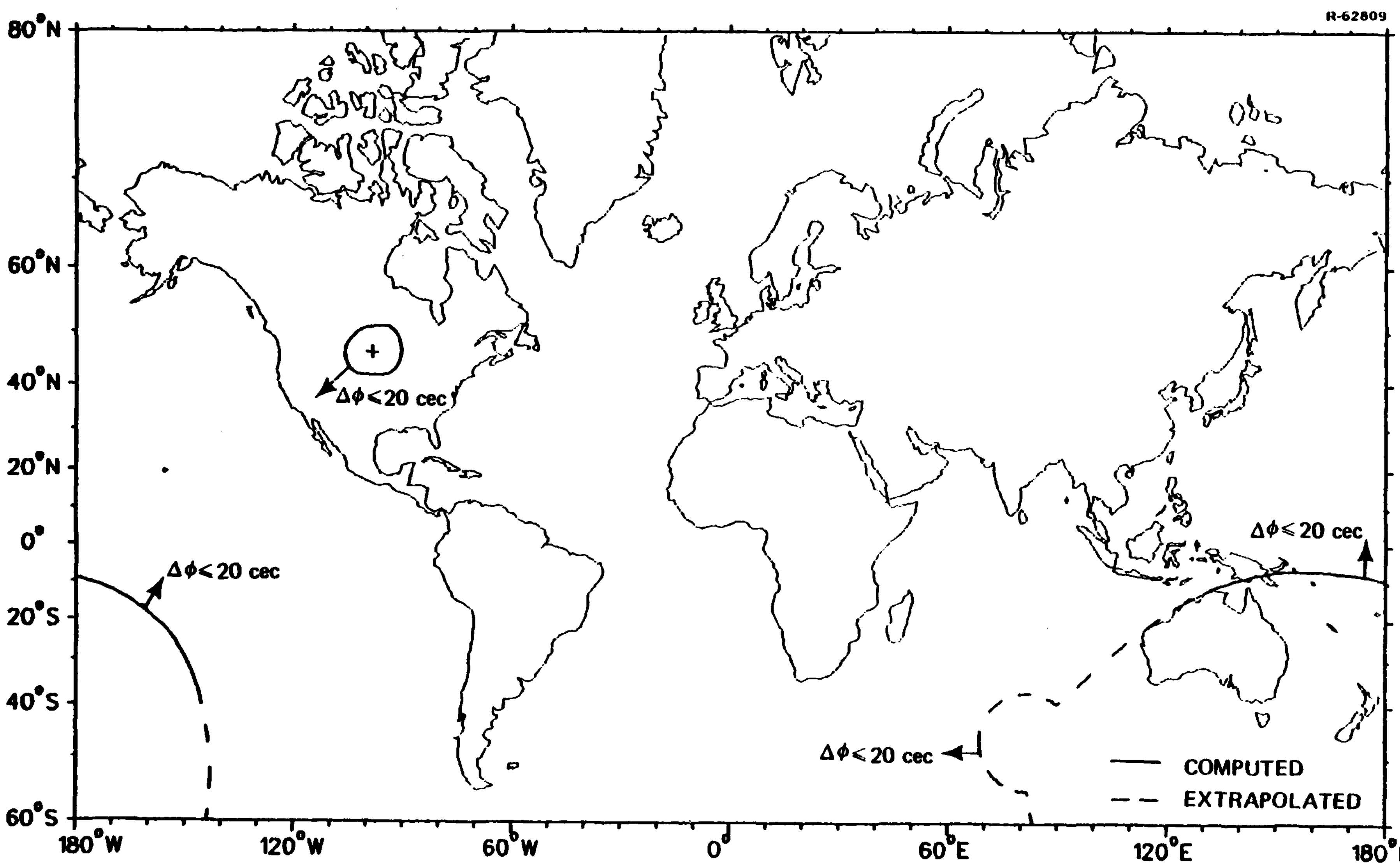
LIBERIA (B) NIGHTTIME MODAL INTERFERENCE



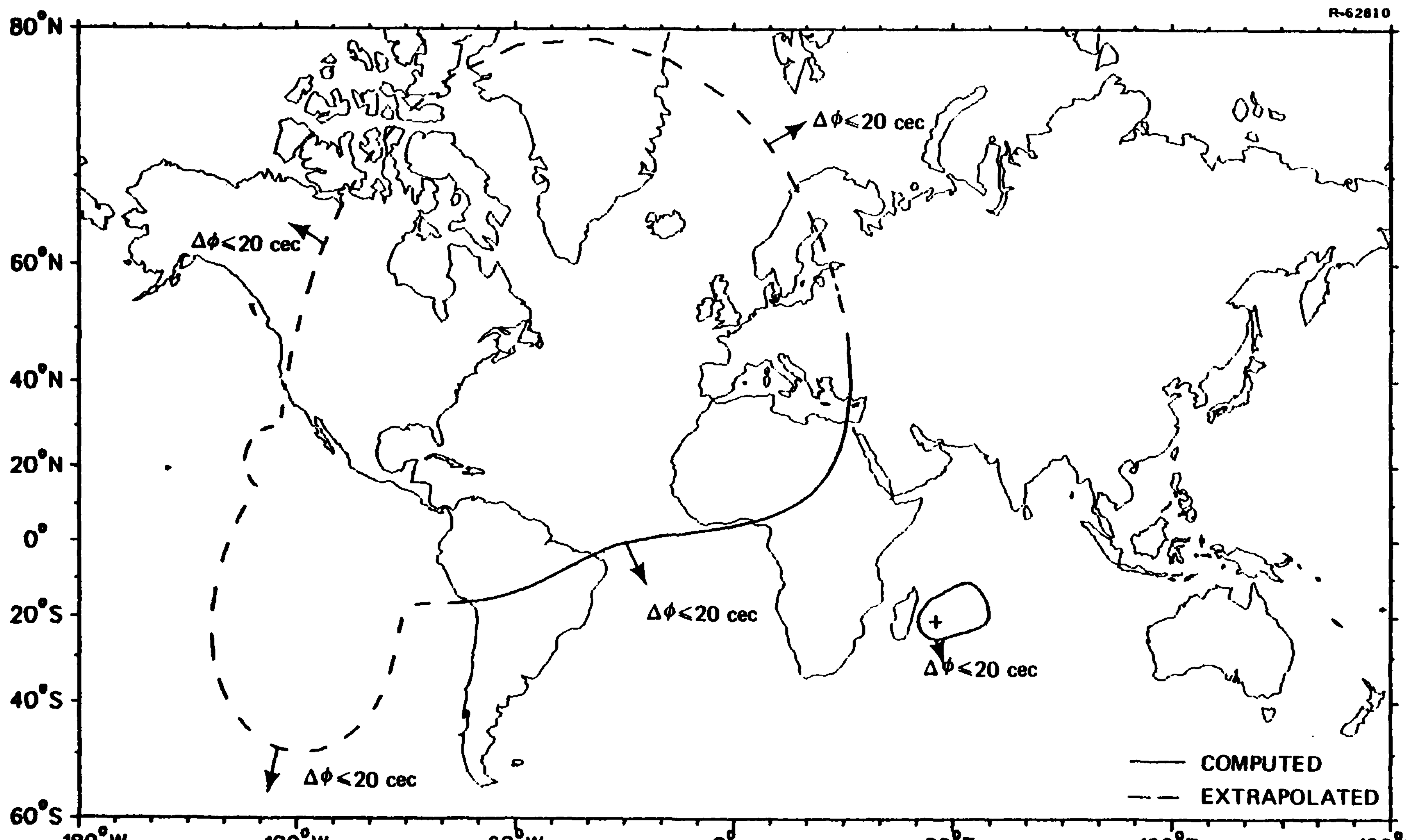
HAWAII (C) NIGHTTIME MODAL INTERFERENCE



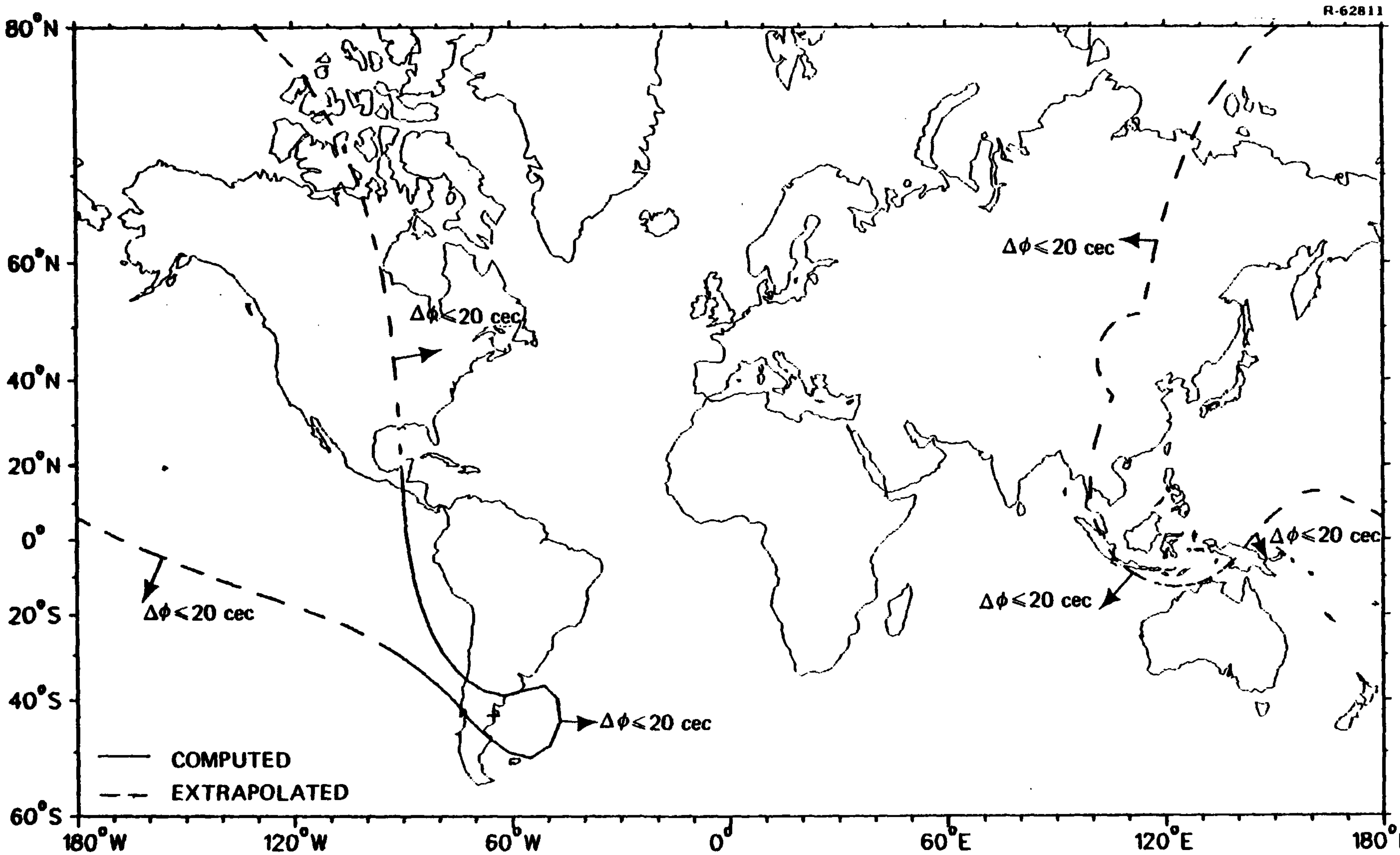
NORTH DAKOTA (D)   NIGHTTIME MODAL INTERFERENCE



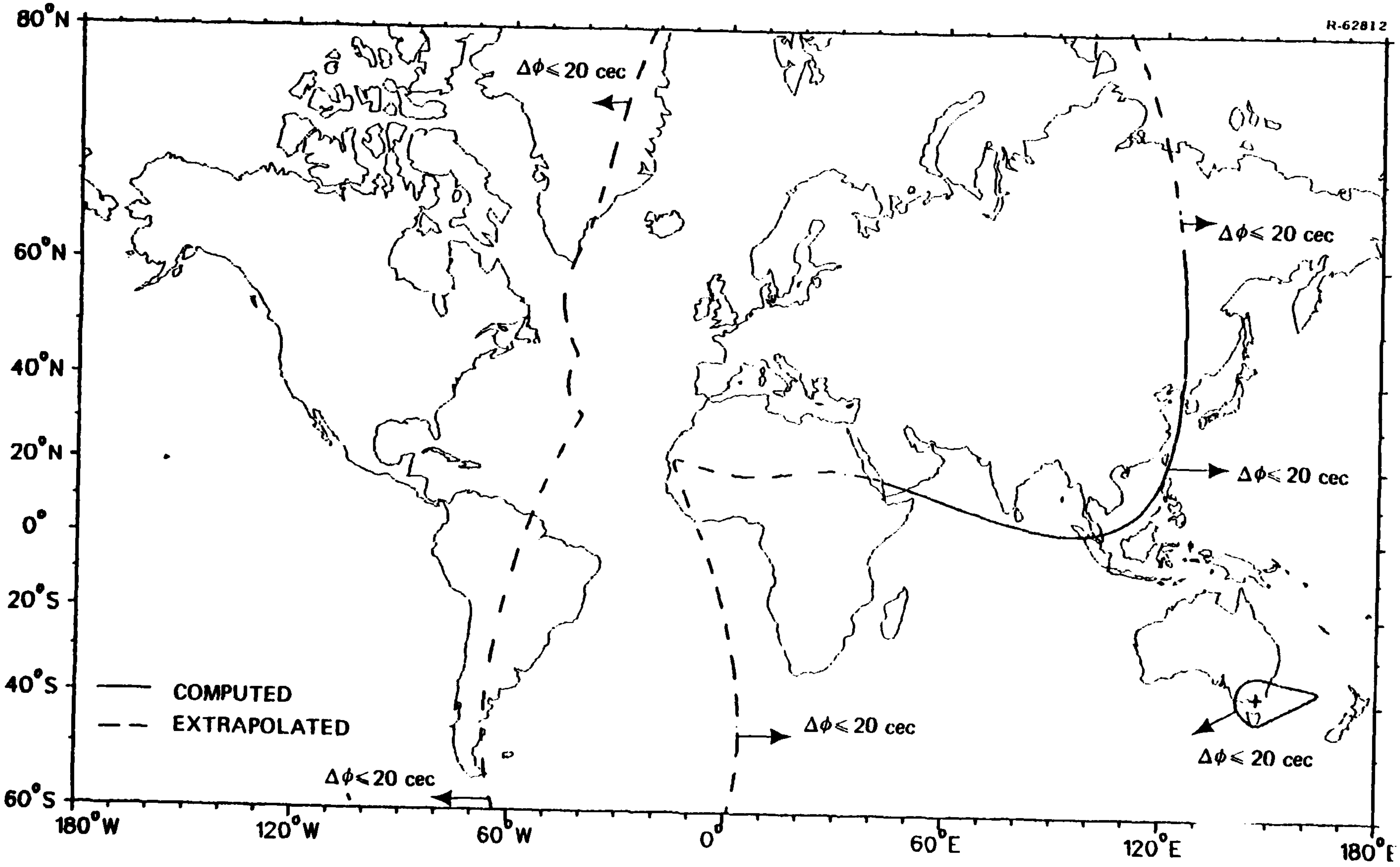
LA REUNION (E) NIGHTTIME MODAL INTERFERENCE



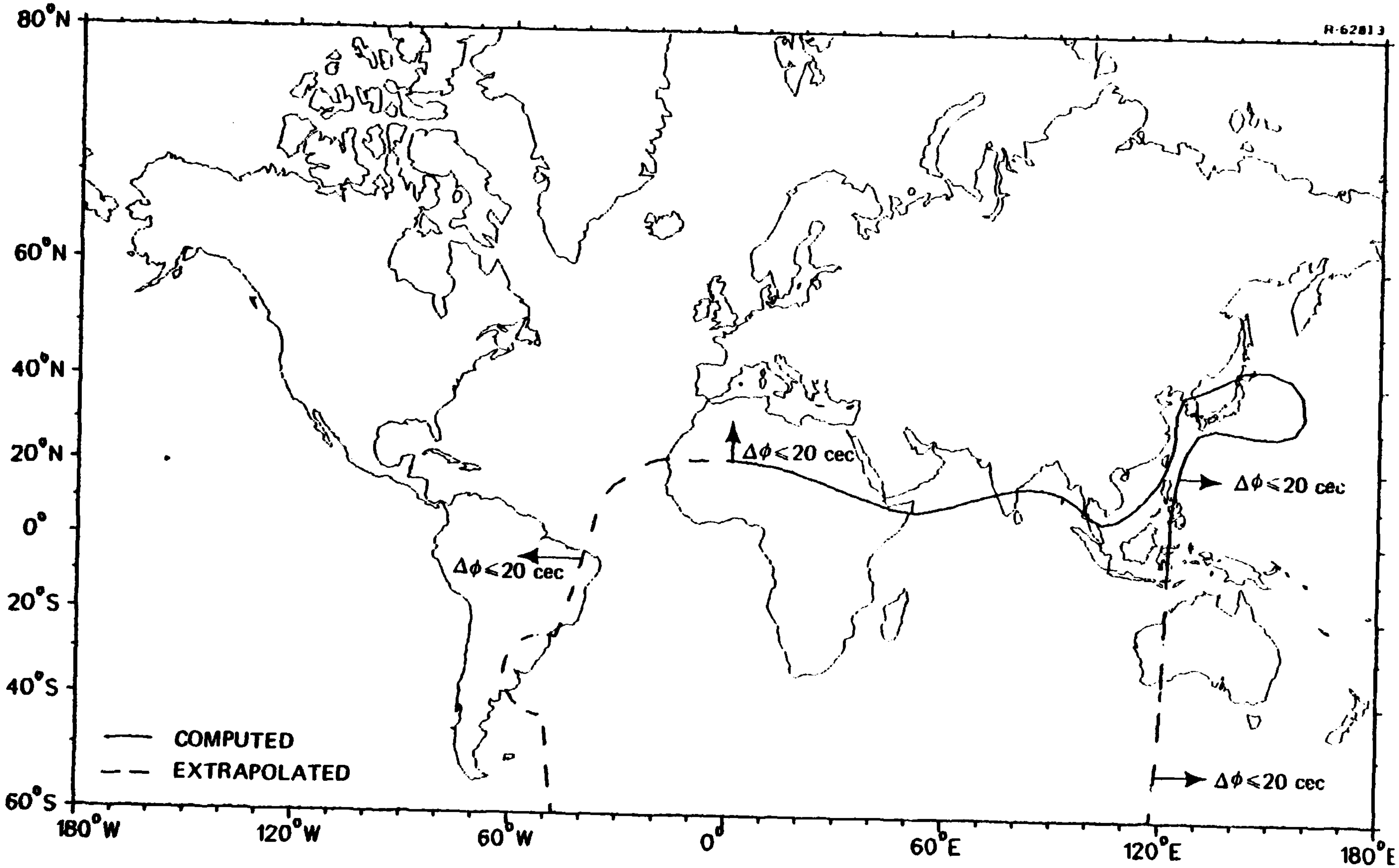
ARGENTINA (F) NIGHTTIME MODAL INTERFERENCE



AUSTRALIA (G) NIGHTTIME MODAL INTERFERENCE



JAPAN (H) NIGHTTIME MODAL INTERFERENCE



REFERENCES

1. Kasper, J.F., Jr., and Hutchinson, C.E., "Omega: Global Navigation by VLF Fix," IEEE Spectrum, Vol. 16, No. 5, May 1979.

2. Morris, P.B., and Cha, M.Y., "OMEGA Propagation Corrections: Background and Computational Algorithms," Department of Transportation, Report No. ONSOD-01-74, December 1974.

3. Bortz, J.E., Sr., Gupta, R.R., Scull, D.C., and Morris, P.B., "OMEGA Signal Coverage Prediction," Navigation: Journal of the Institute of Navigation, Vol. 23, No. 1, Spring 1976.

4. Donnelly, S.F., "Integrated Propagation Prediction Program Documentation," The Analytic Sciences Corporation, Technical Report TR-343-4, November 1973.

5. Ferguson, J.A., "A Report on the Integrated Prediction Program with Nuclear Environment (IPP-2)," NELC Technical Note TN 1890, July 1971.

6. Gupta, R.R., "Theoretical Background of IPP-2," The Analytic Sciences Corporation, Technical Report TR-343-2, February 1973.

7. Berry, L.A. and Herman, J.E., "A Wave Hop Propagation Program for an Anisotropic Ionosphere," Telecommunications Research Report, OT/ITS RR11, Boulder, Colorado, April 1971.

8. Johler, J.R. and Mellecker, C.M., "Computer Program for Theoretical LF, VLF Field Calculations with Spherical Wave Functions of Integer Order," Institute for Telecommunication Sciences, Technical Memorandum No. OT/ITSTM 24, Boulder, Colorado, February 1971.

9. Wait, J.R. and Spies, K.P., "Characteristics of the Earth-Ionosphere Waveguide for VLF Radio Waves," NBS Technical Note No. 300, December 1964.

10. Cheng, D.H.S., "A Survey on Some Mathematical Models of the Very Low Frequency Wave Propagation," Goddard Space Flight Center, Report No. X-521-70-425, December 1970.

REFERENCES (Continued)

11. Budden, K.G., Radio Waves in the Ionosphere, Cambridge University Press, London, 1961.

12. Watt, A.D., VLF Radio Engineering, Pergamon Press, Oxford, 1967.

13. Gupta, R.R., and Donnelly, S.F., "Functional Dependence of Omega Signal Amplitude on Significant Signal Propagation Parameters," The Analytic Sciences Corporation, Technical Information Memorandum TIM-1319-1, October 1978.

14. Gupta, R.R., Griffiths, B.E., and Creamer, P.M., "An Extended Omega Amplitude Prediction Model," The Analytic Sciences Corporation, Technical Report TR-1319-2, December 1979.

15. Rhodes, F.J., "RCA Computer Program for Predicting VLF Communication Coverage; Information Concerning," Naval Research Laboratory, Washington, D.C. 20390, Memorandum No. 5410-518A: FJR: dmc, NRL Prob R01-39, December 1967.

16. International Radio Consultative Committee, "World Distribution and Characteristics of Atmospheric Radio Noise," International Telecommunications Union, C.C.I.R. Report 332, 1964.

17. Stone, D.L., Croghan, R.D., and Crail, A.C., "Computer Program Operational Manual for Atmospheric Predictions," Westinghouse Georesearch Laboratory, June 1970.

18. U.S. Coast Guard Omega Navigation System Operations Detail, "Preliminary Noise Programs Documentation," October 1979.

19. Pierce, J.A., "OMEGA," IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-1, No. 3, December 1965.

20. Donnelly, S.F., "CONTOUR Program Documentation," The Analytic Sciences Corporation, Technical Report TR-735-2-2, April 1977.

21. Donnelly, S.F., "COMPOSE Program Documentation," The Analytic Sciences Corporation, Technical Report TR-735-2-1, April 1977.